Transverse phase space studies of XFEL 250 pC beam vs laser shaping

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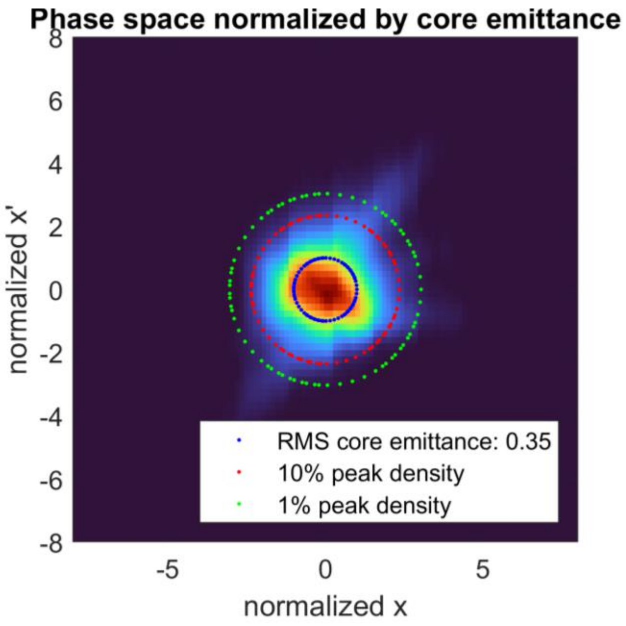
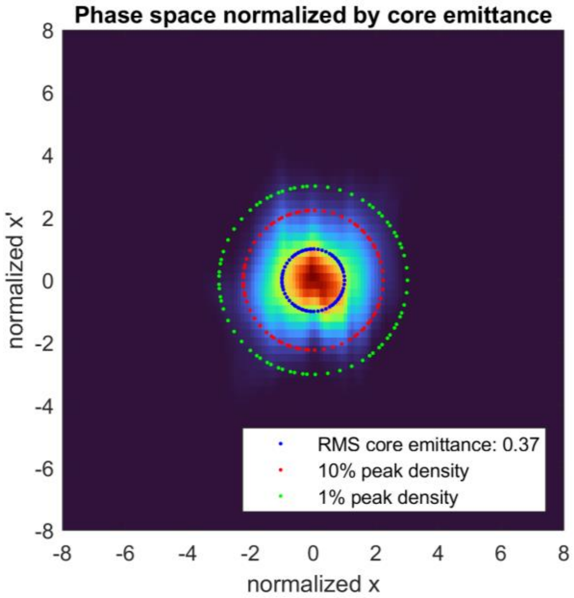
1.06.2021





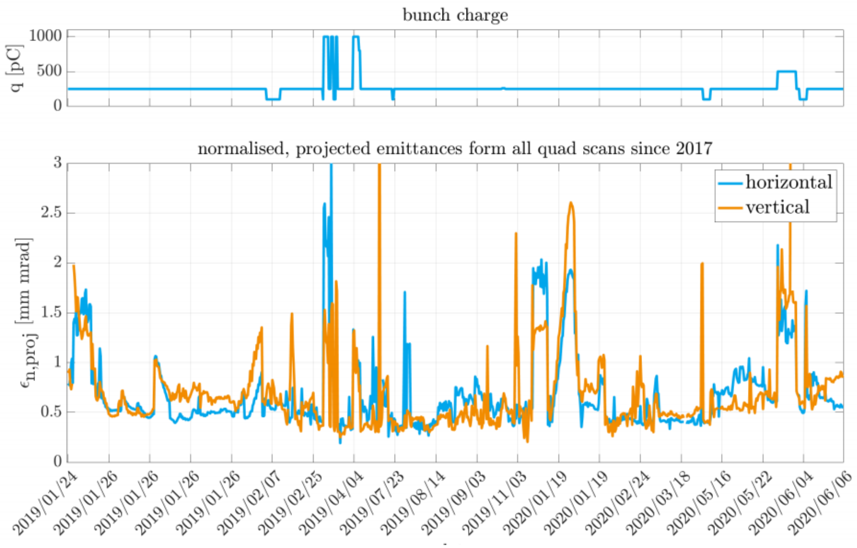
Outline

- Motivation
- Transverse phase space
- Analysis of simulations
- Analysis of experiments
- Summary

Motivation

How to compare emittance values between XFEL injector and PITZ

- 250 pC emittance statistics
  - PITZ: ~0.47-0.8 mm.mrad
    - Slit scan → 2D phase space distribution → emittance
  - XFEL: ~0.35 – 0.8 mm.mrad
    - Phase advance scan → <xx>, <xx’>, <x’x’> (if no tomography)
    - Emittance depends on beam size calculation (rms or Gaussian fitting)
  - How to compare the two?



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

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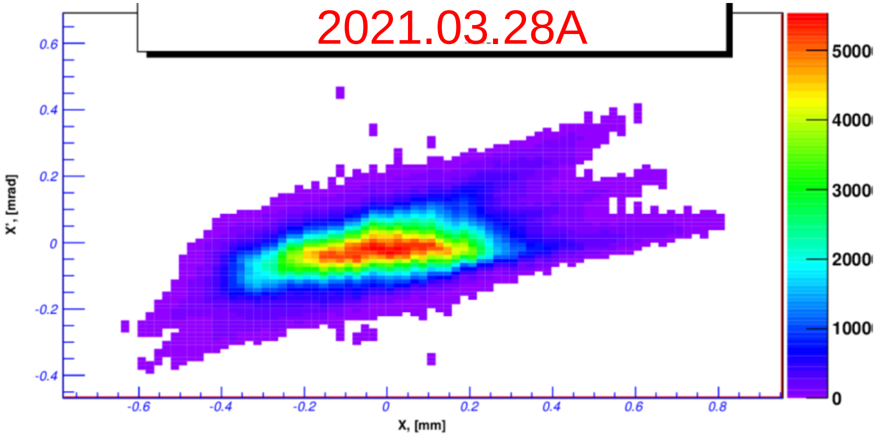
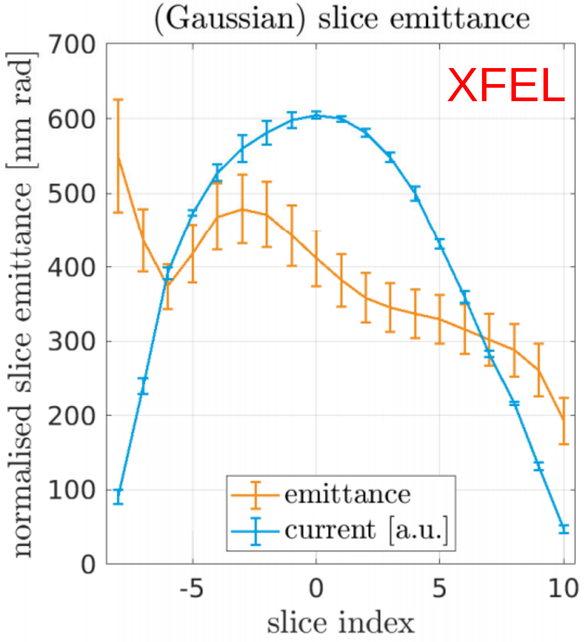
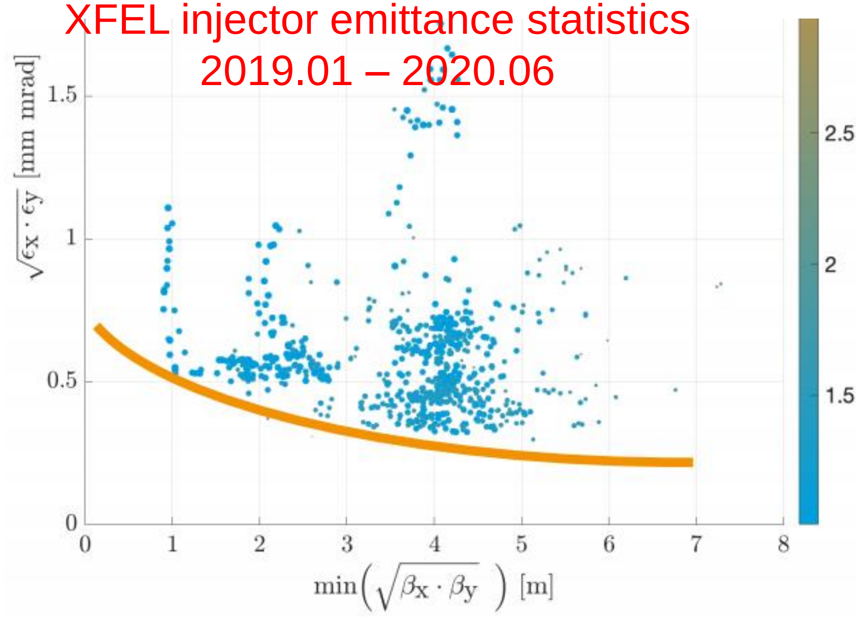




XFEL injector emittance statistics

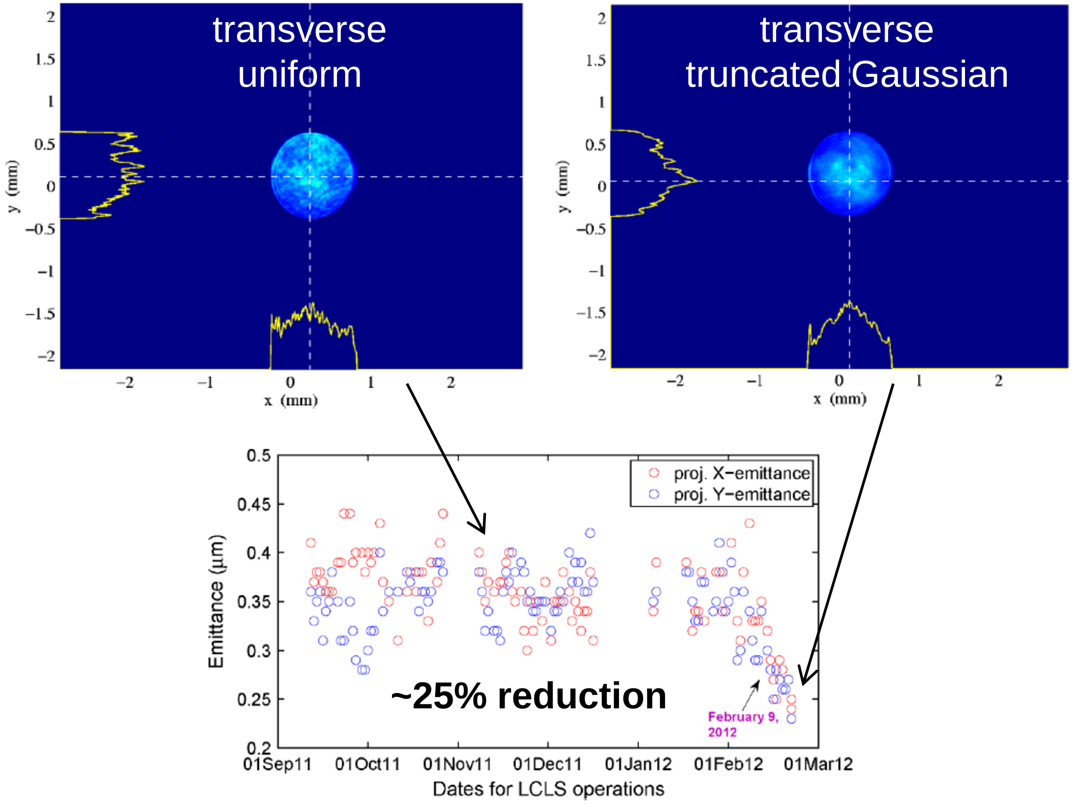
2019.01 – 2020.06



LCLS injector with Gaussian truncation optimization

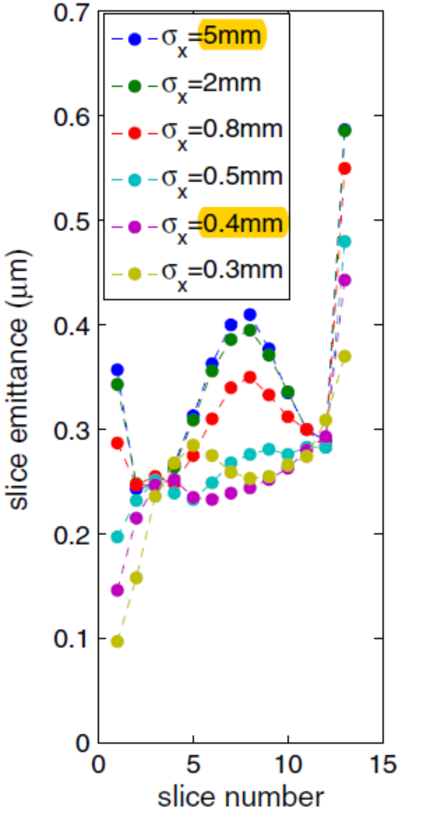
LCLS-I injector example

- **2012**, LCLS experience: (PRST AB 15, 090701)
  - 150 pC, ~1.3 ps (rms) laser
  - Uniform → 1.1-σ Gaussian truncation



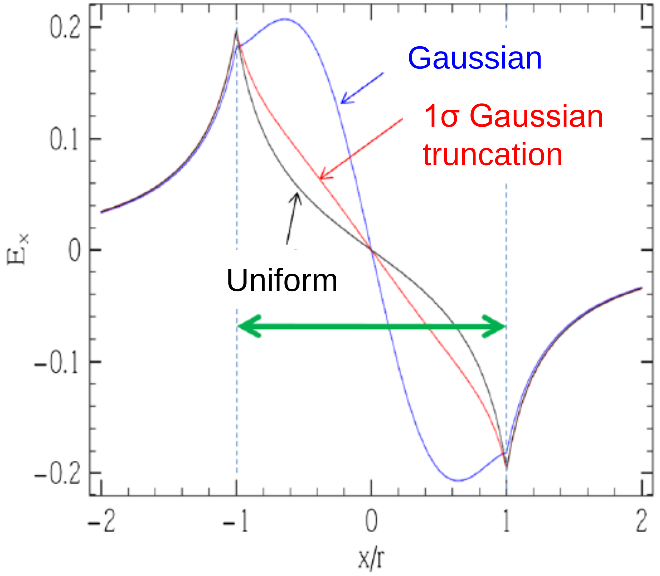
Experiment: projected emittance

Fixed BSA
Vary laser rms size



Simulated slice emittance

Pancake emission regime
z/x=0.1

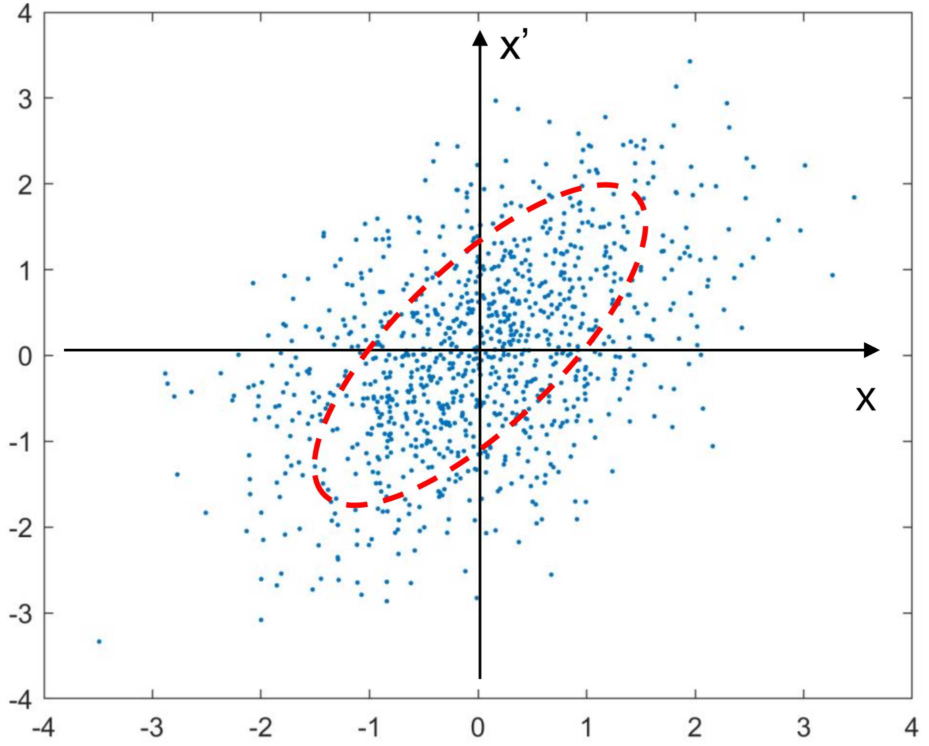


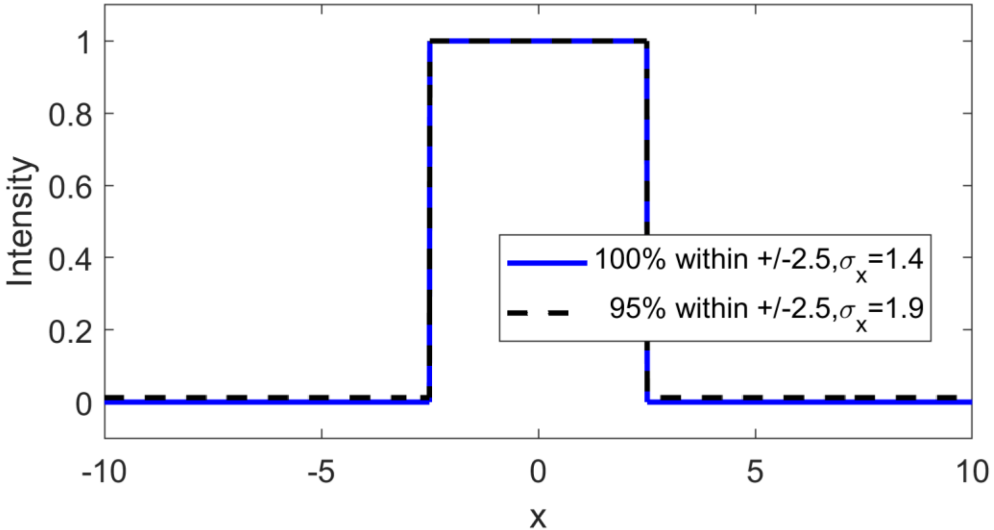
Comparison of transverse space charge linearization

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, $\varepsilon_{rms} = \gamma x^2 + 2\alpha x x' + \beta x'^2$
  - Pro: easy to describe beam in real space
  - Con: not a good way to describe beam quality in phase space, i.e. phase space density (2D)
    - If the 95% phase space distribution is the same, but outside 5% particles become very bad, then ε_{rms} becomes very bad, just like the rms size calculation of 1D distribution.

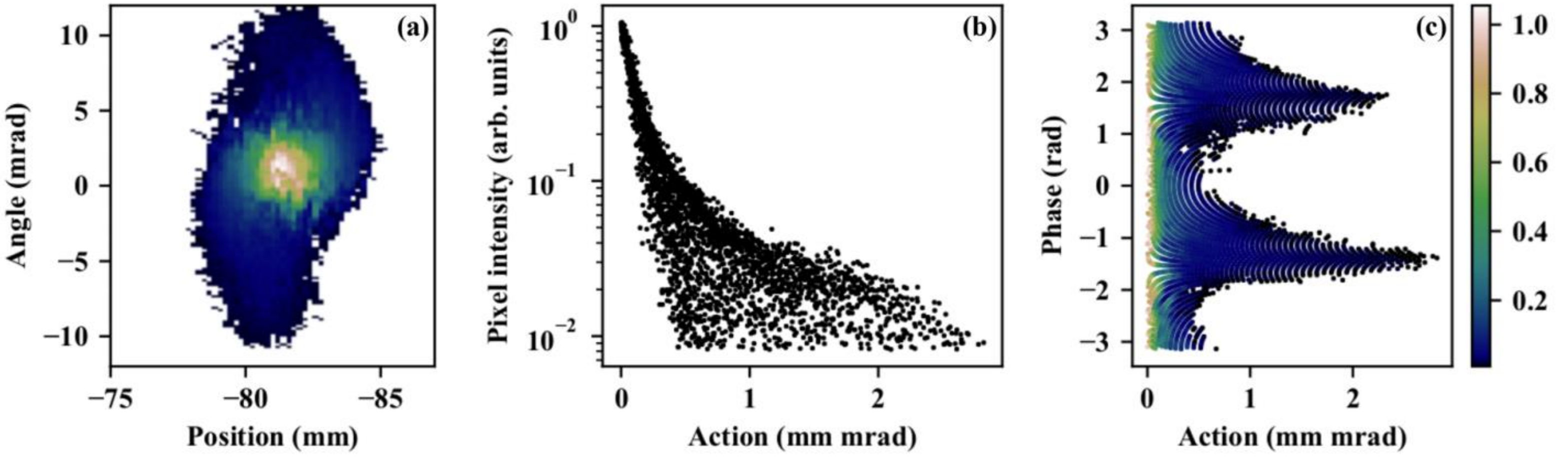


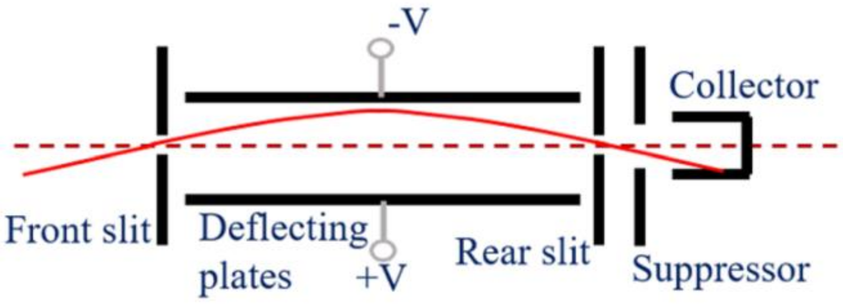


Action and phase analysis of phase space

Another method to analyze phase space data

- Get to know this idea during an interview
  - Method is published, the author is also employed by our group
    - 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



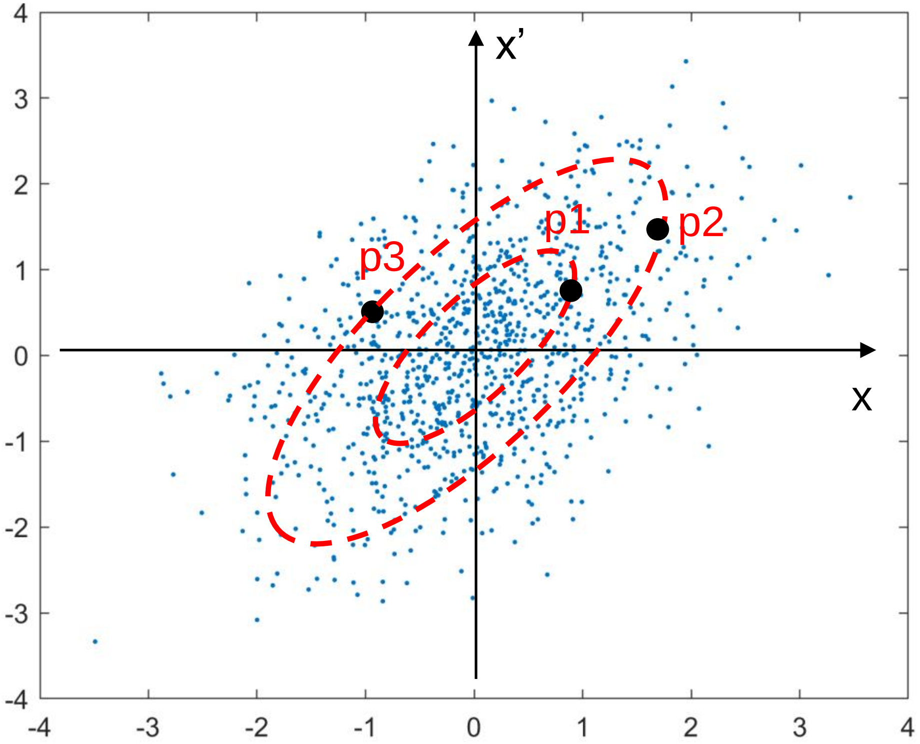


2.1 MeV H^-, v=0.048c

Phase space transformation

Action and phase coordinates

- Transform into new coordinates
  - Action (ellipse area/2pi)
    - $J_i = \frac{1}{2}\left(\gamma x_i^2 + 2\alpha x_i x_i' + \beta {x_i'}^2\right)$
      - $\varepsilon_{rms} = \frac{1}{N}\sum_i J_i$
  - Phase
    - $J_i = \frac{1}{2\beta}\left(x_i^2 + (\alpha x_i + \beta x_i')^2\right)$
    - $\phi_i = \tan^{-1}\frac{\alpha x_i + \beta x_i'}{x_i}$
  - Pro: project particles to the J axis, i.e. dQ/J, better describes phase space density.
  - Con: cannot describe beam motion in real space



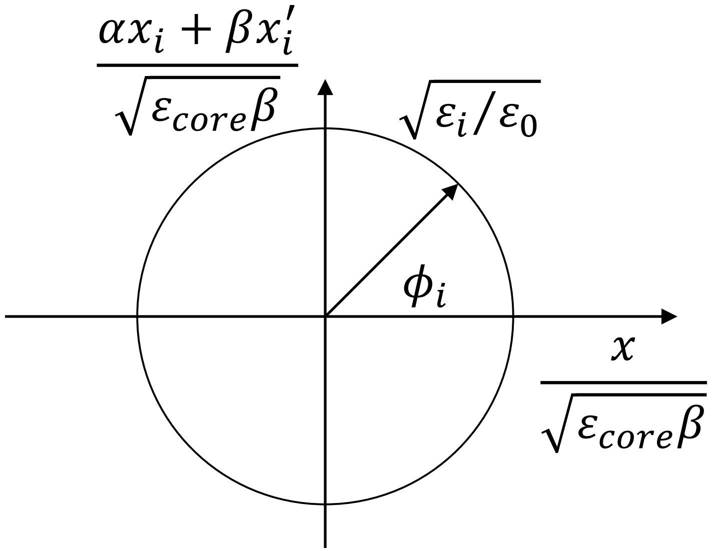
Phase space transformation

Action and phase coordinates

- Core emittance analysis
  - Assume the phase space core is a good approximation of Gaussian distribution
  - $dQ = \frac{Q}{2\pi\varepsilon_0} \exp\left(-\frac{\gamma x_i^2 + 2\alpha x_i x_i' + \beta x_i'^2}{2\varepsilon_0}\right) dx dx'$

    $= \frac{Q}{\varepsilon_0} \exp\left(-\frac{J}{\varepsilon_0}\right) dJ$
  - Fit exponential density decay → core emittance ε_0
    - Non Gaussian 'halo particles' does not matter anymore in calculating core emittance
    - Similar to XFEL emittance calculation by using Gaussian fitted beam size

- Phase space renormalization
  - $\varepsilon_i = \gamma x_i^2 + 2\alpha x_i x_i' + \beta x_i'^2$
  - $\frac{\varepsilon_i}{\varepsilon_0} = \left(\frac{x}{\sqrt{\varepsilon_0 \beta}}\right)^2 + \left(\frac{\alpha x_i + \beta x_i'}{\sqrt{\varepsilon_0 \beta}}\right)^2$



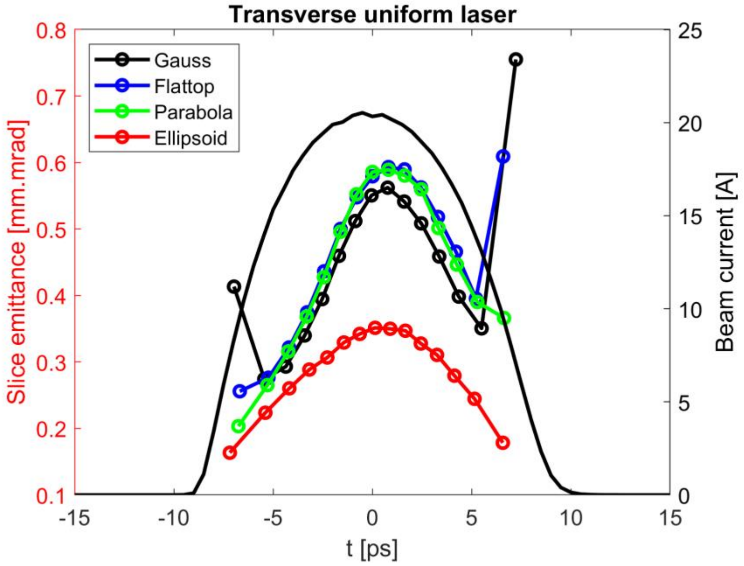
250 pC simulations with the PITZ beamline vs laser shaping

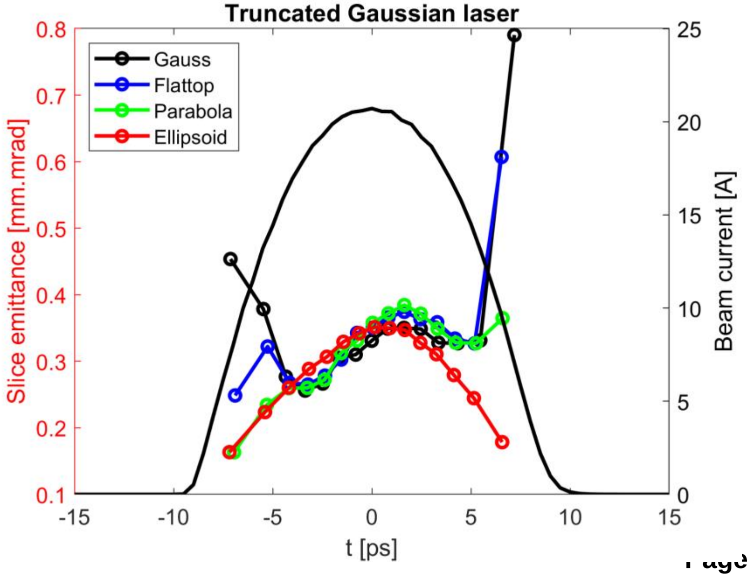
250 pC simulation vs laser shapes

gun 6.3 MeV/c, booster exit ~19.5 MeV/c

- Thermal emittance setting: 1 mm.mrad/mm (measurements)
- Laser rms size 0.25 mm
  - Gaussian: 6 ps FWHM (close to MBI laser values)
  - Flattop/Parabolic/Ellipsodial, final peak current ~20 A
    - Tune duration to get same emission peak current
- Projected emittance
  - 6-20% reduction on **100% emittance**
  - 10-16% reduction on **95% emittance**
  - Negligible difference (+/-3%) on **core emittance**

	Spatial uniform			Spatial 1σ truncation		
	100%	95%	Core	100%	95%	Core
Gaussian	0.70	0.40	0.29	0.66	0.36	0.32
Flattop	0.60	0.39	0.29	0.53	0.33	0.31
Parabolic	0.53	0.37	0.28	0.42	0.31	0.31
Ellipsoidal	0.40	0.30	0.30	0.40	0.30	0.30


Transverse uniform laser

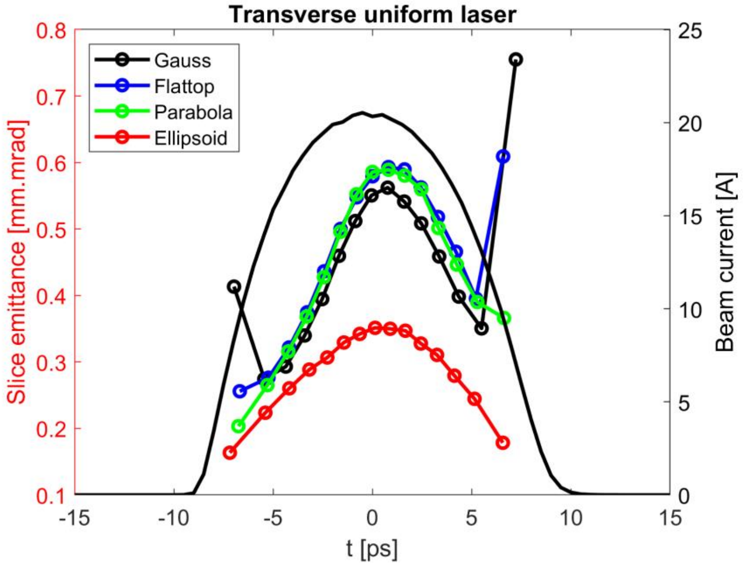

Truncated Gaussian laser

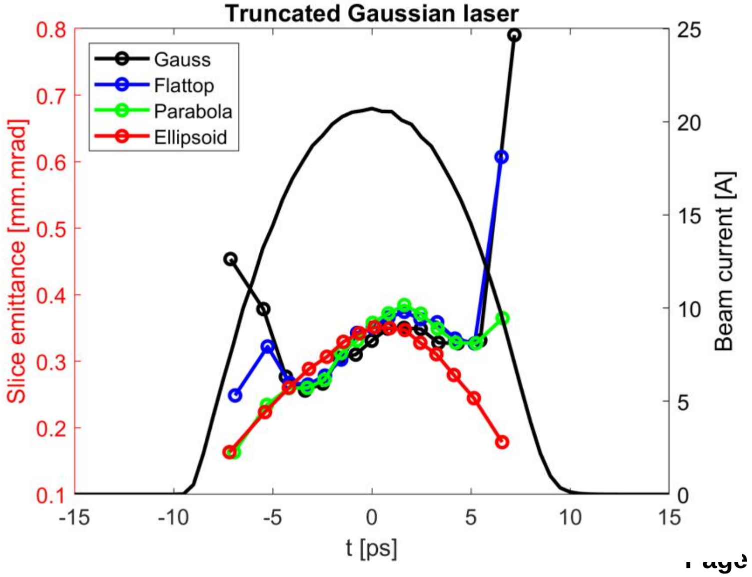
250 pC simulation vs laser shapes

gun 6.3 MeV/c, booster exit ~19.5 MeV/c

- Thermal emittance setting: 1 mm.mrad/mm (measurements)
- Laser rms size 0.25 mm
  - Gaussian: 6 ps FWHM (close to MBI laser values)
  - Flattop/Parabolic/Ellipsodial, final peak current ~20 A
    - Tune duration to get same emission peak current
- Central slice emittance
  - 42% reduction on **<u>100% emittance</u>**
  - 33% reduction on **<u>95% emittance</u>**
  - Negligible difference (+/-3%) on **<u>core emittance</u>**

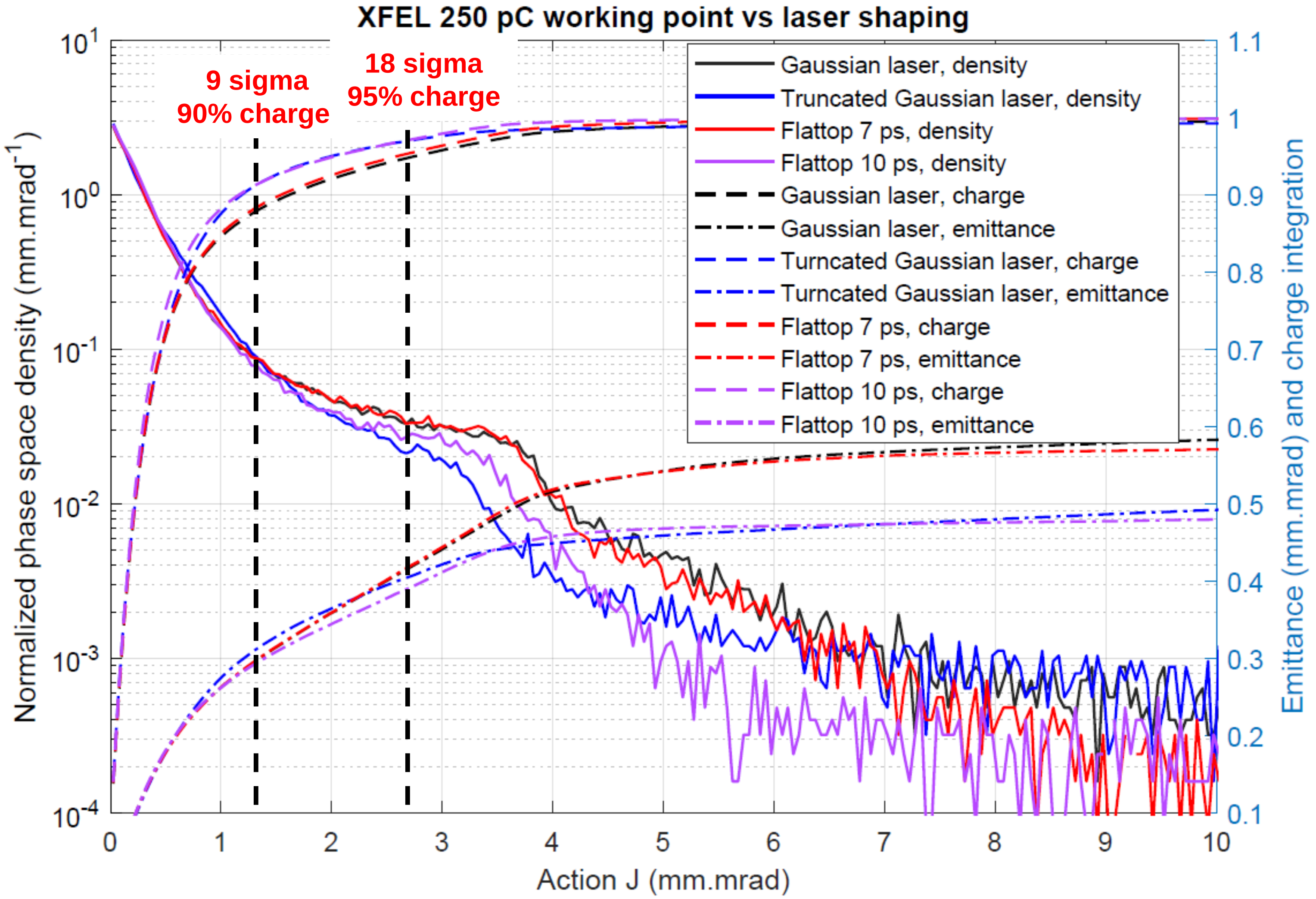
	Spatial uniform			Spatial 1σ truncation		
	100%	95%	Core	100%	95%	Core
Gaussian	0.53	0.38	0.26	0.30	0.25	0.27
Flattop	0.56	0.39	0.26	0.32	0.26	0.28
Parabolic	0.56	0.40	0.25	0.33	0.26	0.27
Ellipsoidal	0.34	0.28	0.29	0.34	0.28	0.29





250 pC vs laser shaping

Projected phase space

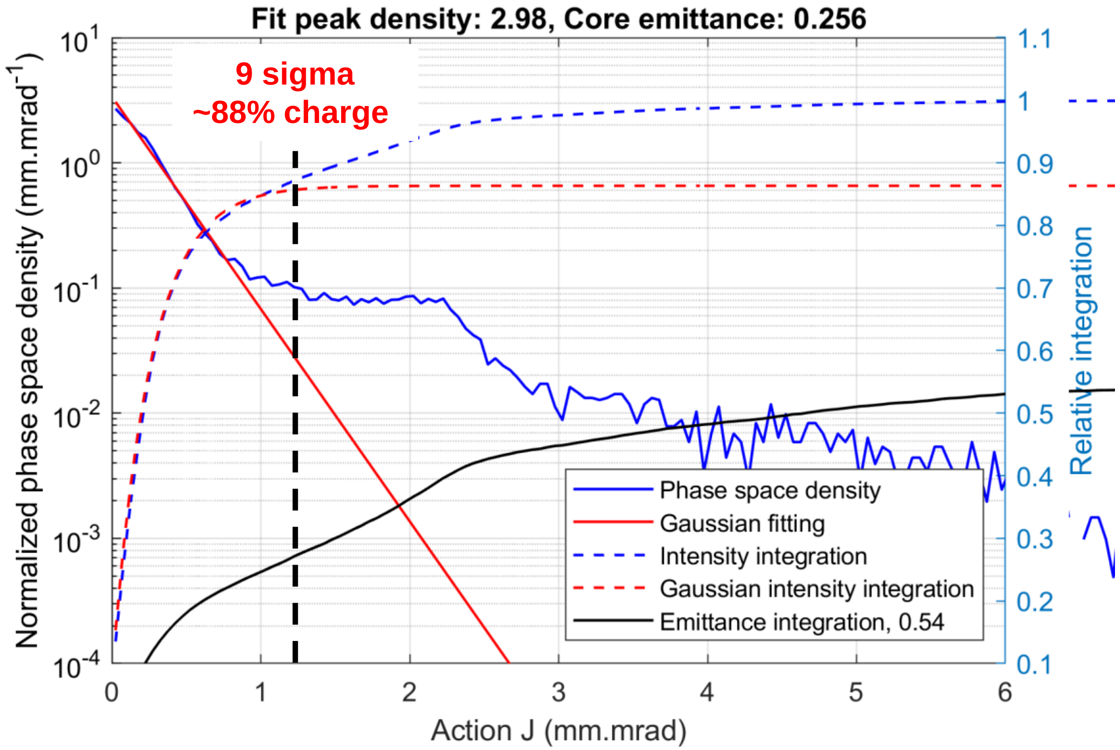


- Four laser shapes
  - Gaussian 6 ps FWHM, trans. Uniform
  - Gaussian 6 ps FWHM, trans. 1sigma truncation
  - Flattop 7 ps FWHM, 2 ps rising edge, trans. Uniform
  - Flattop 10 ps FWHM, 2 ps rising edge, trans. Uniform
- Core emittance is ~0.3 mm.mrad
  - 9 sigma phase space area → action J =1.3 mm.mrad
  - Phase space density no difference within 9 sigma phase space

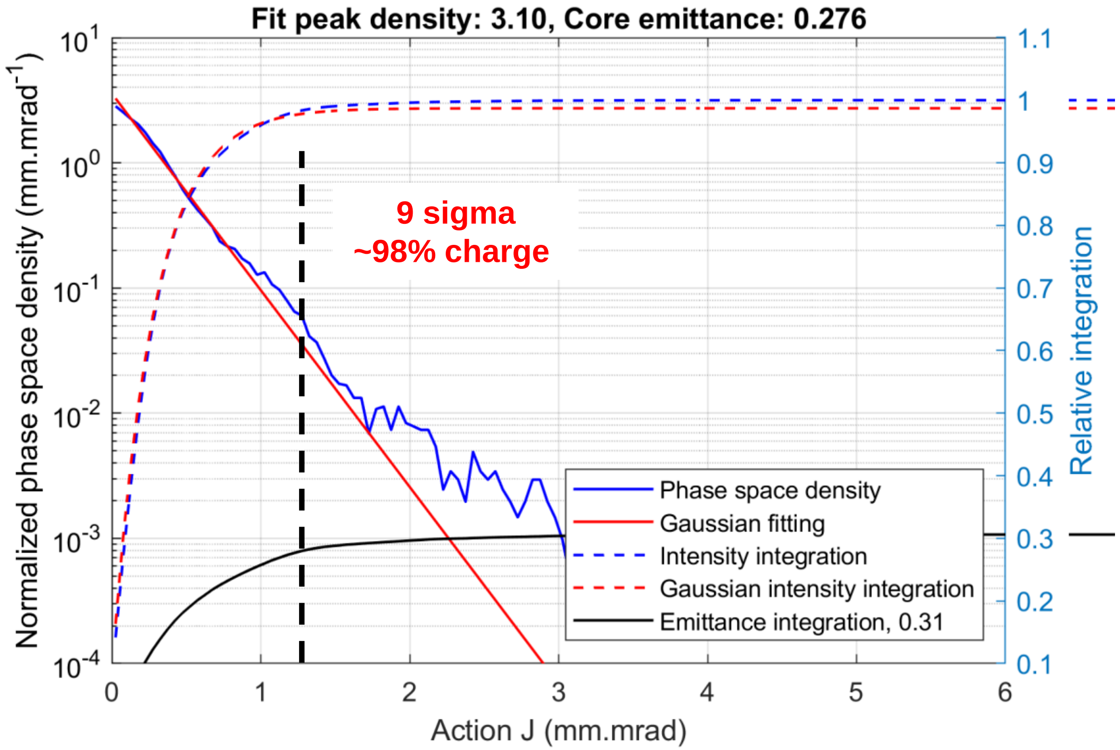
250 pC vs laser spatial shaping

Central slice emittance

Core emittance ~0.27 mm.mrad, 9 sigma phase space action J =1.2 mm.mrad



Spatial uniform

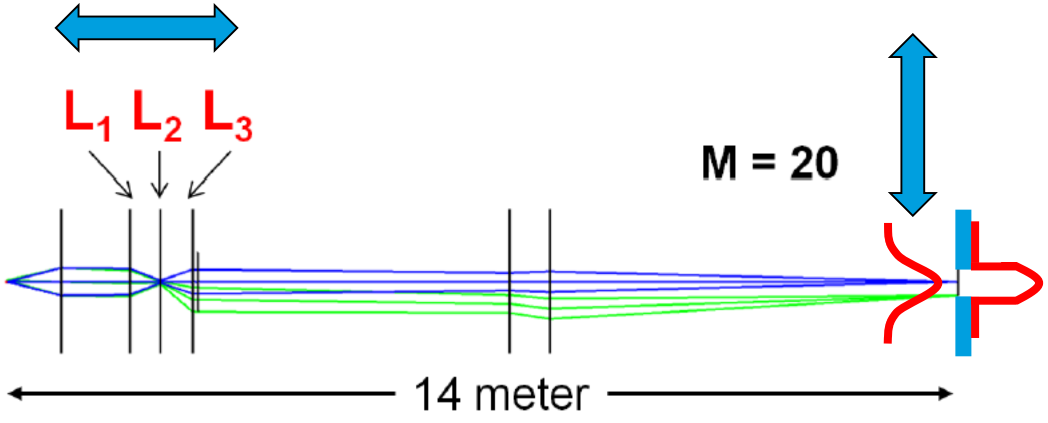


Spatial 1-sigma truncation

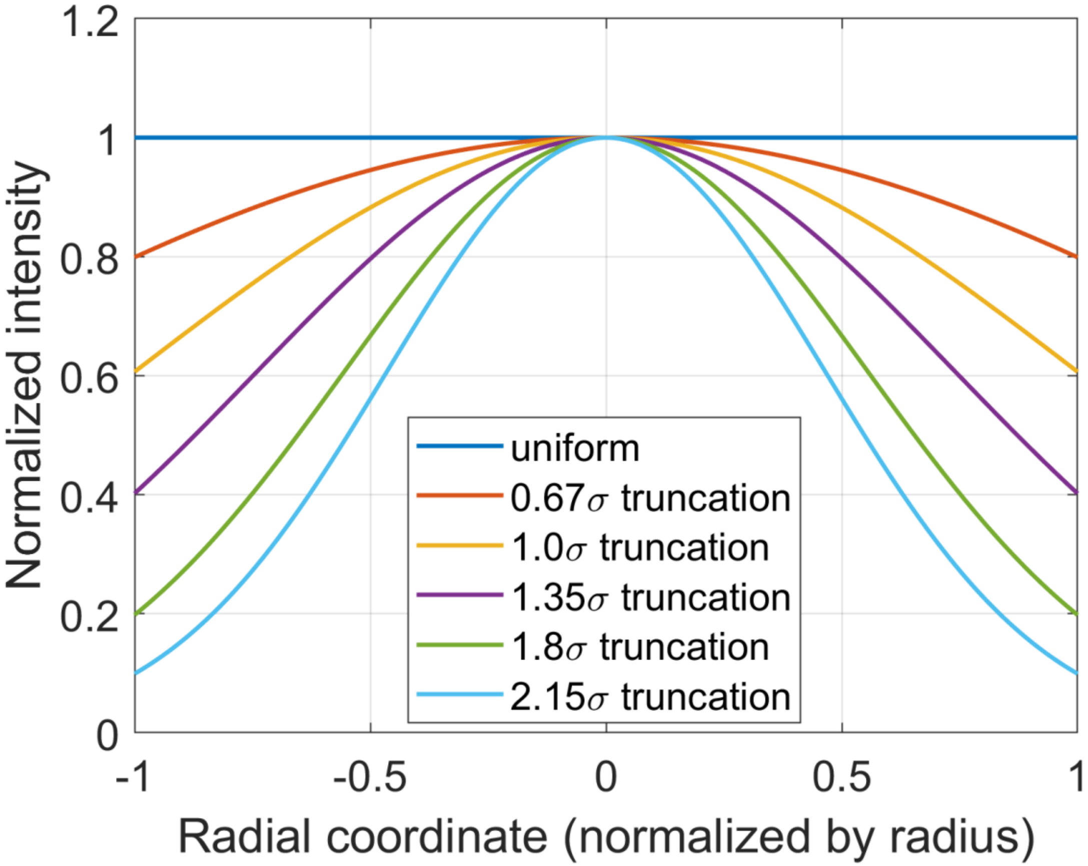
250 pC experiment

Preparation of Truncated Gaussian Laser Pulses

Zoom telescope and beam shaping aperture

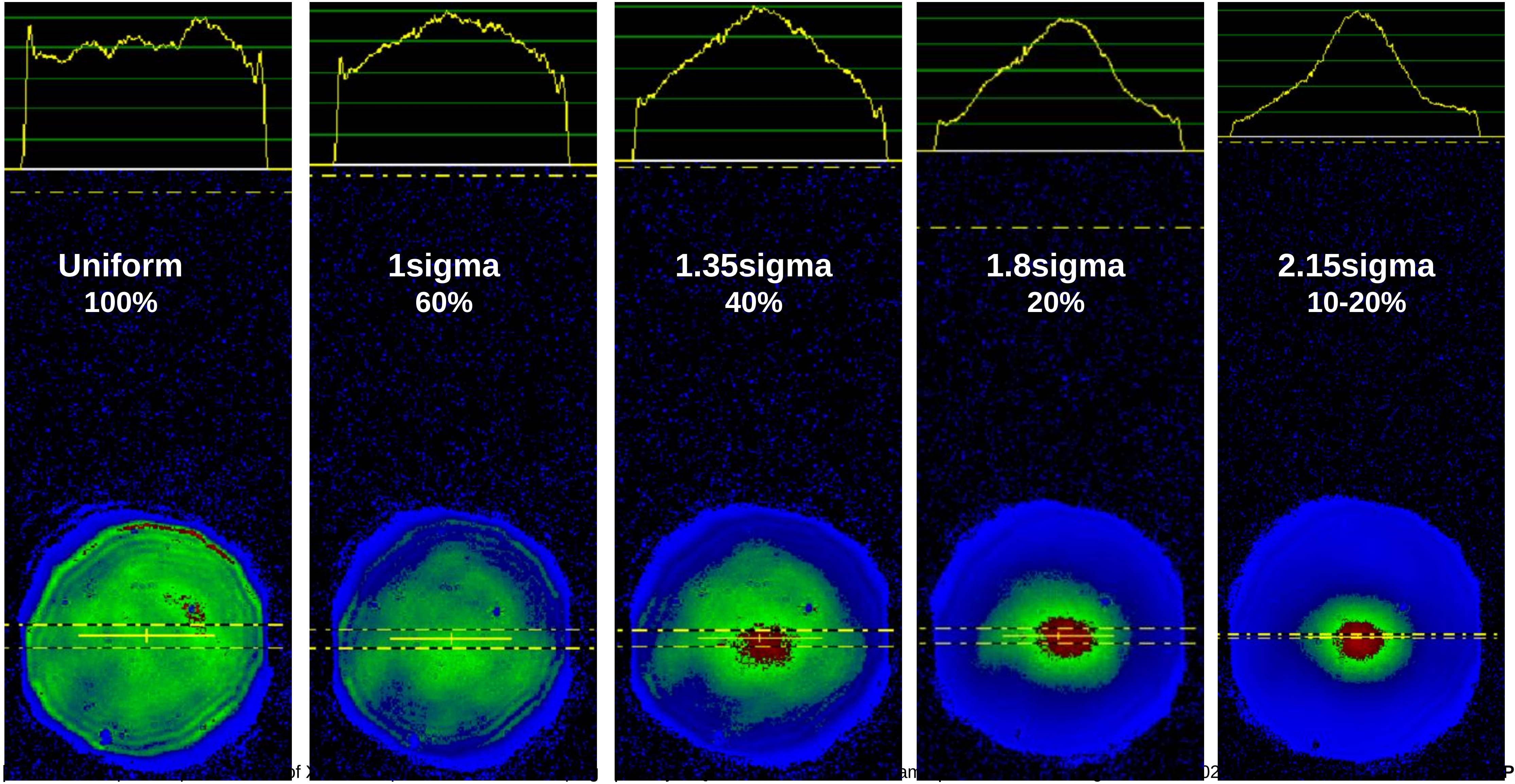


- Zoom telescope: laser transverse size on beam shaping aperture (BSA) is adjusted to achieve truncation to varying degrees
- Advantage: Varying truncation can be studies for fixed BSA size; quickly adjustable



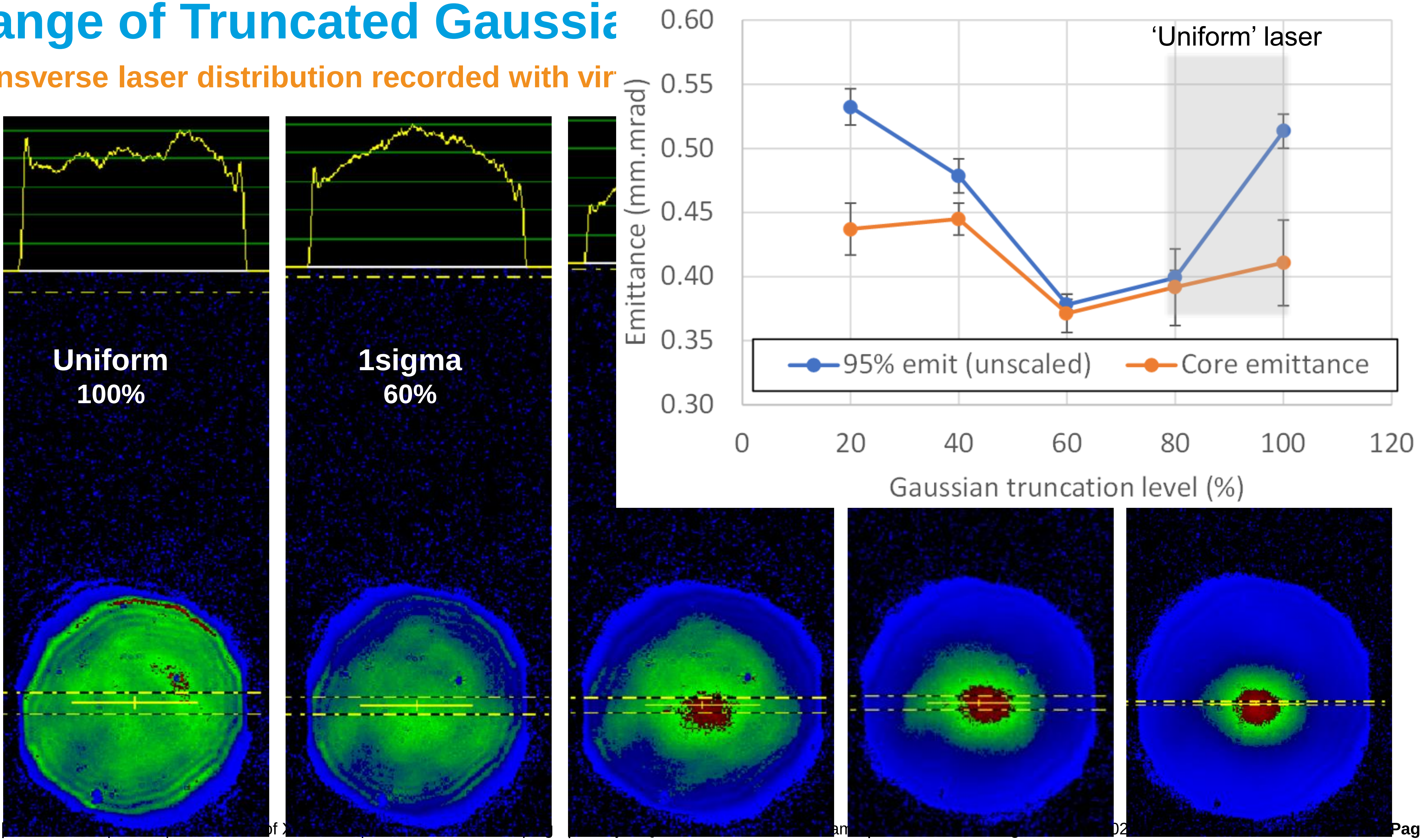
Range of Truncated Gaussians in this Study

Transverse laser distribution recorded with virtual cathode camera



Range of Truncated Gaussia

Transverse laser distribution recorded with vir



250 pC (Uniform)

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

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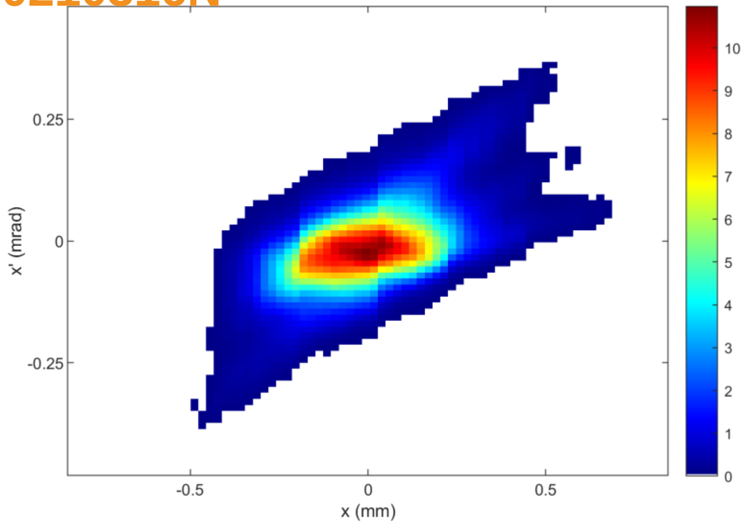

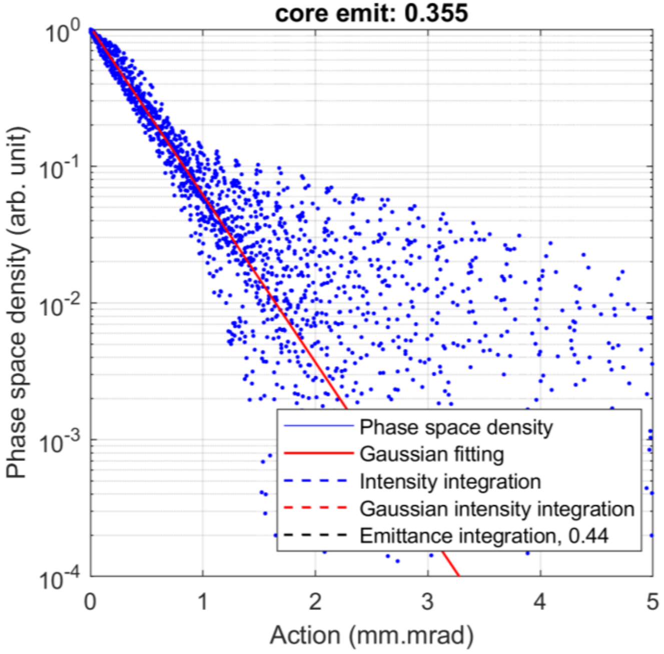

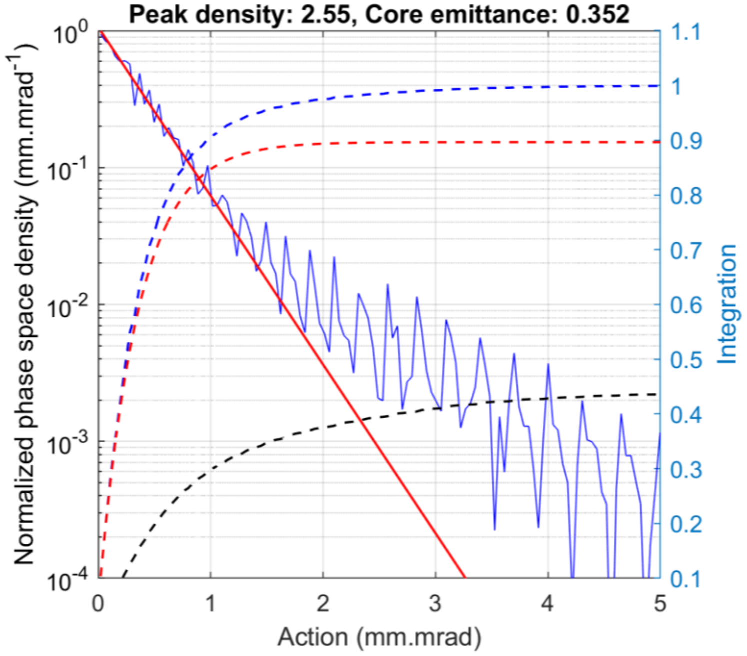

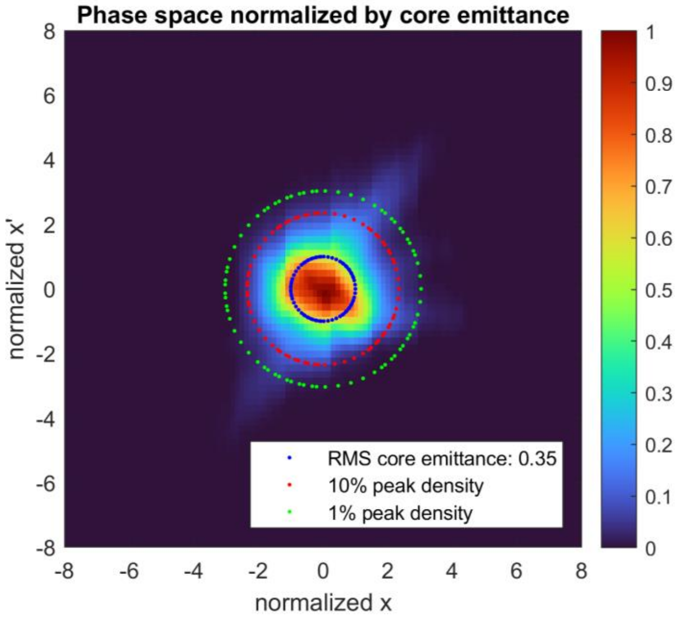

	simu	exp	errbar
95% emit	0.40	0.46	0.01
90% emit	0.29	0.34	/
Core	0.29	0.36	0.005
Peak density	3.00	2.4	0.1
Core ratio	86%	86%	/

Peak density $\frac{dQ/Q}{dJ}$

250 pC (1σ truncation)

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

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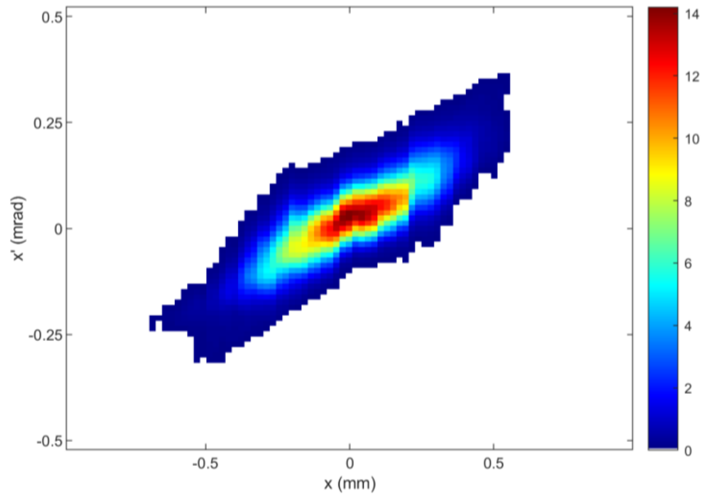
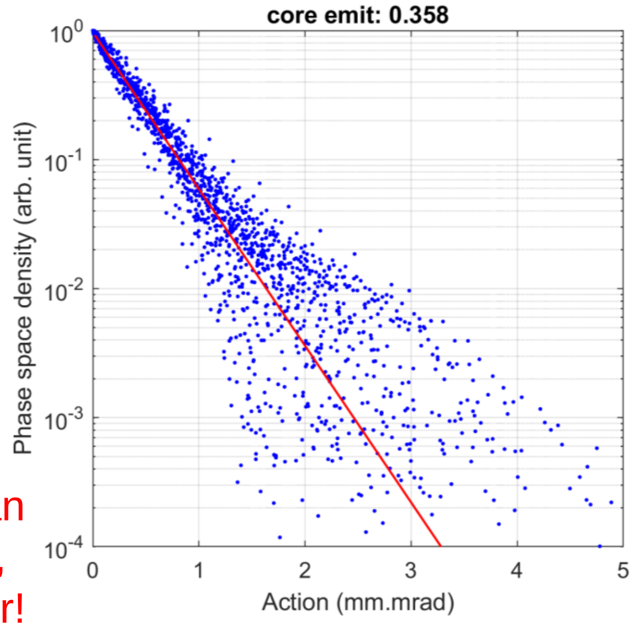
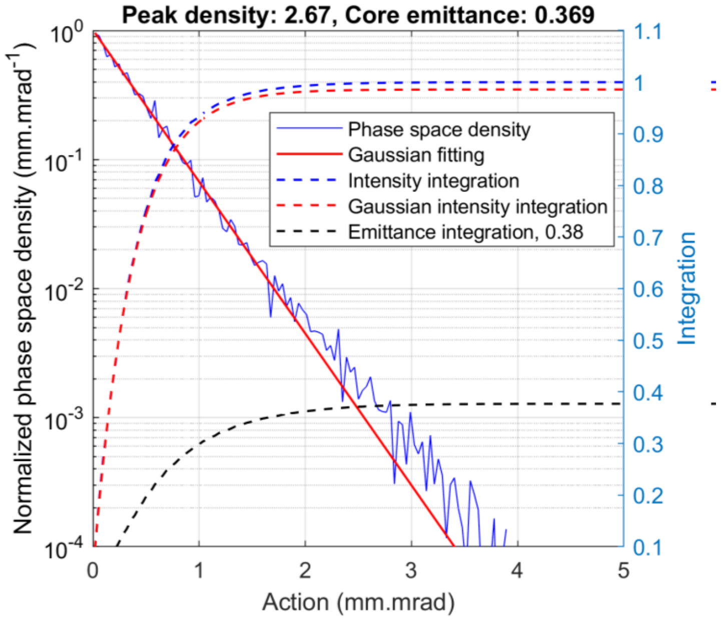
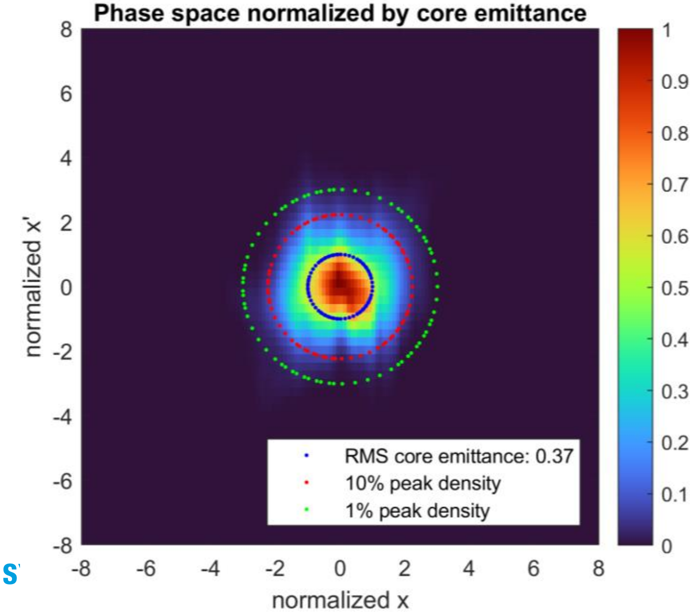


Non-Gaussian tails reduced, core is similar!





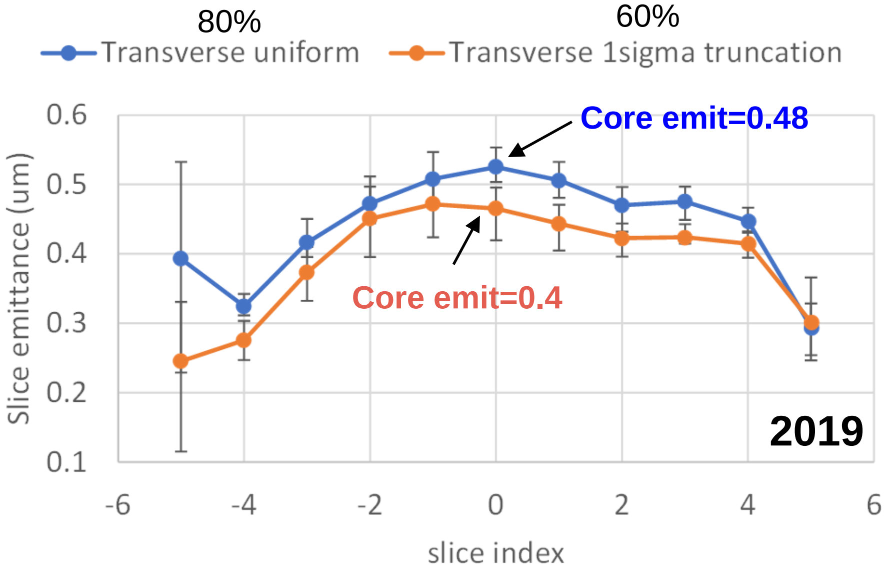


	simu	exp	errbar
95% emit	0.36	0.38	0.004
90% emit	0.28	0.31	/
Core	0.31	0.37	0.01
Peak density	3.0	2.51	0.10
Core ratio	91%	93%	/

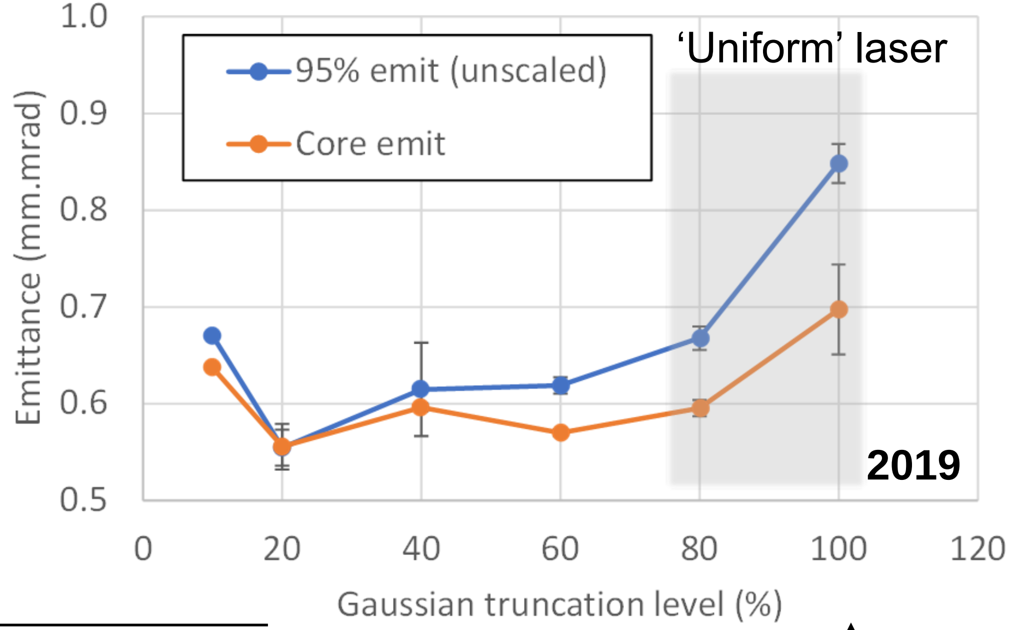
Comparison between 250 pC to 500 pC

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

- 250 pC slice emittance measurements



- 500 pC laser truncation measurements



In continuous shifts.

- 250 pC vs 500 pC measurements

	250 pC (BSA1)			500 pC (BSA1.3)		
	‘Uniform’ 80% 2021	‘Uniform’ 80% 2019	Truncation 60% 2019	‘Uniform’ 80% 2021	‘Uniform’ 80% 2019	Truncation 20% 2019
~95% emit	0.46	0.52	0.38	0.64	0.67	0.56
Core	0.36	0.39	0.37	0.51	0.60	0.56
Peak density	2.4	2.4	2.5	1.7	1.5	1.7
Core charge	86%	93%	93%	86%	90%	90%
	10 um slit	**50 um slit**		**10 um slit**	**50 um slit**	

Not in the same year.

The better results from 2021, might be due to better beam, or 10 um slit effect.

Summary

- Action and phase analysis is applied to PITZ data for core emittance, which is comparable with XFEL injector emittance values based on Gaussian beam fitting.
- **Simulations** show **95-100% emittance** can be reduced by laser spatial shaping (**up to 30-40%**), but **core emittance is not sensitive** to laser shaping, laser shaping optimizes **non-Gaussian tails (5-15% charge)** in phase space.
- Experiments show 95-100% emittance of **250 pC** is optimized with **60% truncation** laser, **500 pC** is optimized with **20% truncation** laser.
  - 100-95% emittances do show large reduction for both projected and slice emittance (up to 35%).
  - Projected core emittance is not sensitive to laser shaping, as expected by simulations.
  - Slice core emittance does show a ~16% reduction due to laser spatial shaping, but projected core emittances are very close → Slice emittance measurements are not as often as projected emittance, not sure it's real or just coincidence.
  - Best proj. core emittance for 250 pC and 500 pC from 2021
    - 250 pC: ~**0.36 mm.mrad** (ideal simulations ~**0.3 mm.mrad**)
    - 500 pC: ~**0.51 mm.mrad** (ideal simulations ~**0.4 mm.mrad**)

~20% higher.