Incorporating space charge in the transverse phase space matching and tomography at PITZ.

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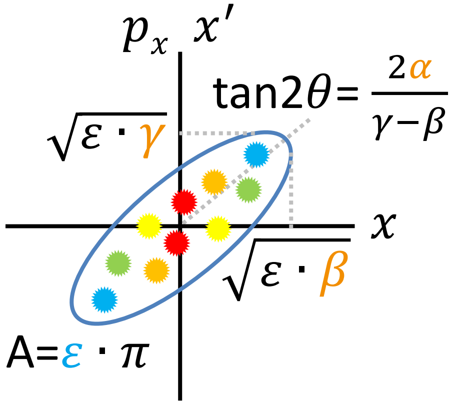
Outline

- Basic concepts and motivation:
  - Transverse phase space
  - Space charge
  - PITZ facility
  - Phase Space Tomography (PST)
- Beam matching with space charge: <u>periodic</u> and <u>dense</u> lattices
- Beam matching with space charge: <u>aperiodic</u> and <u>sparse</u> lattices
- Space charge in the tomographic reconstruction
- Summary and outlook

Transverse phase space

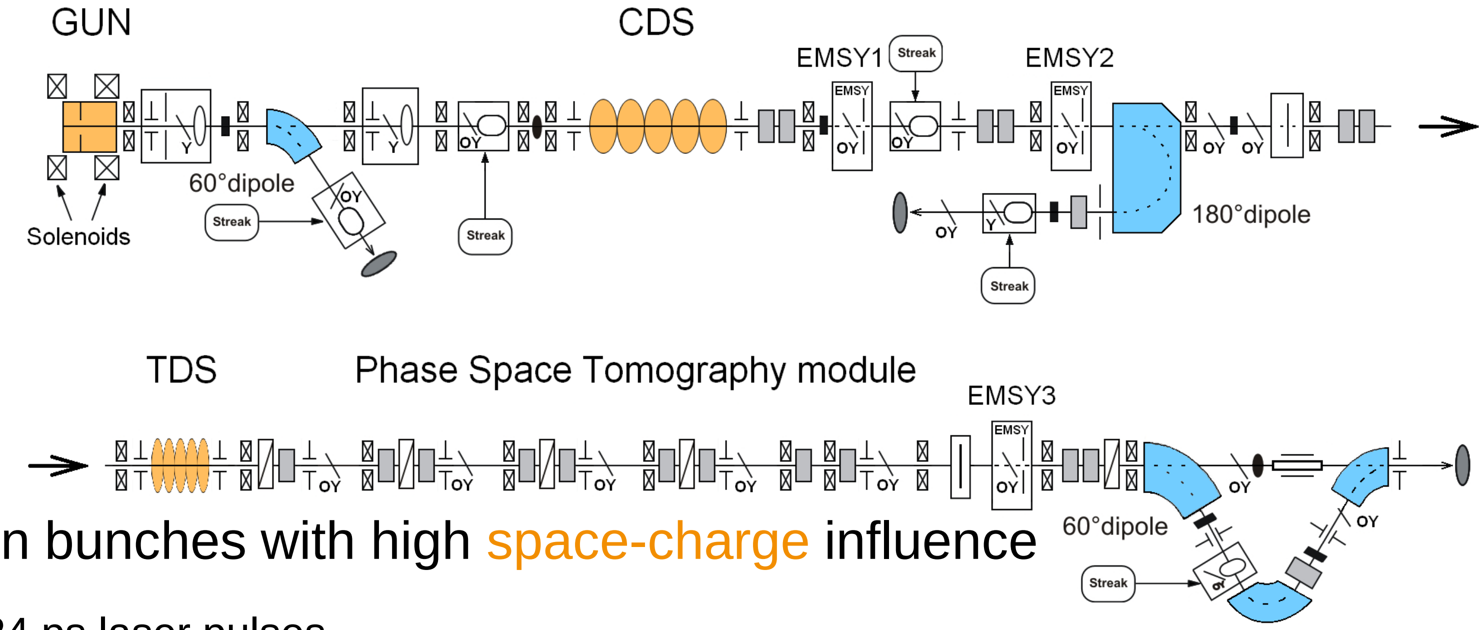
- Crucial factor for the performance of various accelerator applications
  - Free-electron laser (FEL – SASE): affects gain length, output power, minimum achievable wavelength, transverse coherence, brilliance
  - Plasma wakefield acceleration: affects beam quality, feasibility of staging
- Goal: optimization and detailed characterization

- Represents the dynamic state of a beam's particles in the transverse direction: (x, p_x, y, p_y) or (x, x', y, y')
- Characterized by emittance, Courant-Snyder parameters
- Transformed with the particles' motion along the machine described by:
  - the transfer matrix (linear geometrical transformation)
  - the phase advance (particle relocation inside the bunch)



Space charge

- Coulomb repulsion among the particles of the beam
- Electromagnetic fields (only direct considered, no image fields) from a uniform cylindrical bunch:
  - $E_r(r,\zeta) = \frac{Ir}{2\pi\epsilon_0 R^2 \beta_{rel} c} g(\zeta)$:
    - linear dependence on transverse position in the bunch
    - max at bunch center – min at head / tail
  - $F_r = q(E_r - \beta_{rel} c B_\theta) = ... = qE_r/\gamma_{rel}^2$
- Dependence on bunch current, radius and energy
- Impacts: beam transport, quality and measurements
- Motivation: time-efficient methods to compensate its effects



> Electron bunches with high space-charge influence

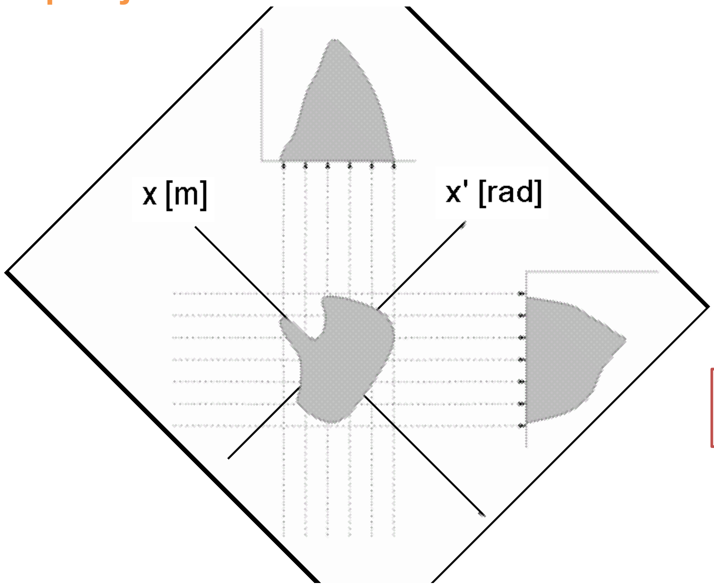
- 2 – 24 ps laser pulses
- 20 pC – 1 nC bunch charge
- < 25 MeV/c momentum

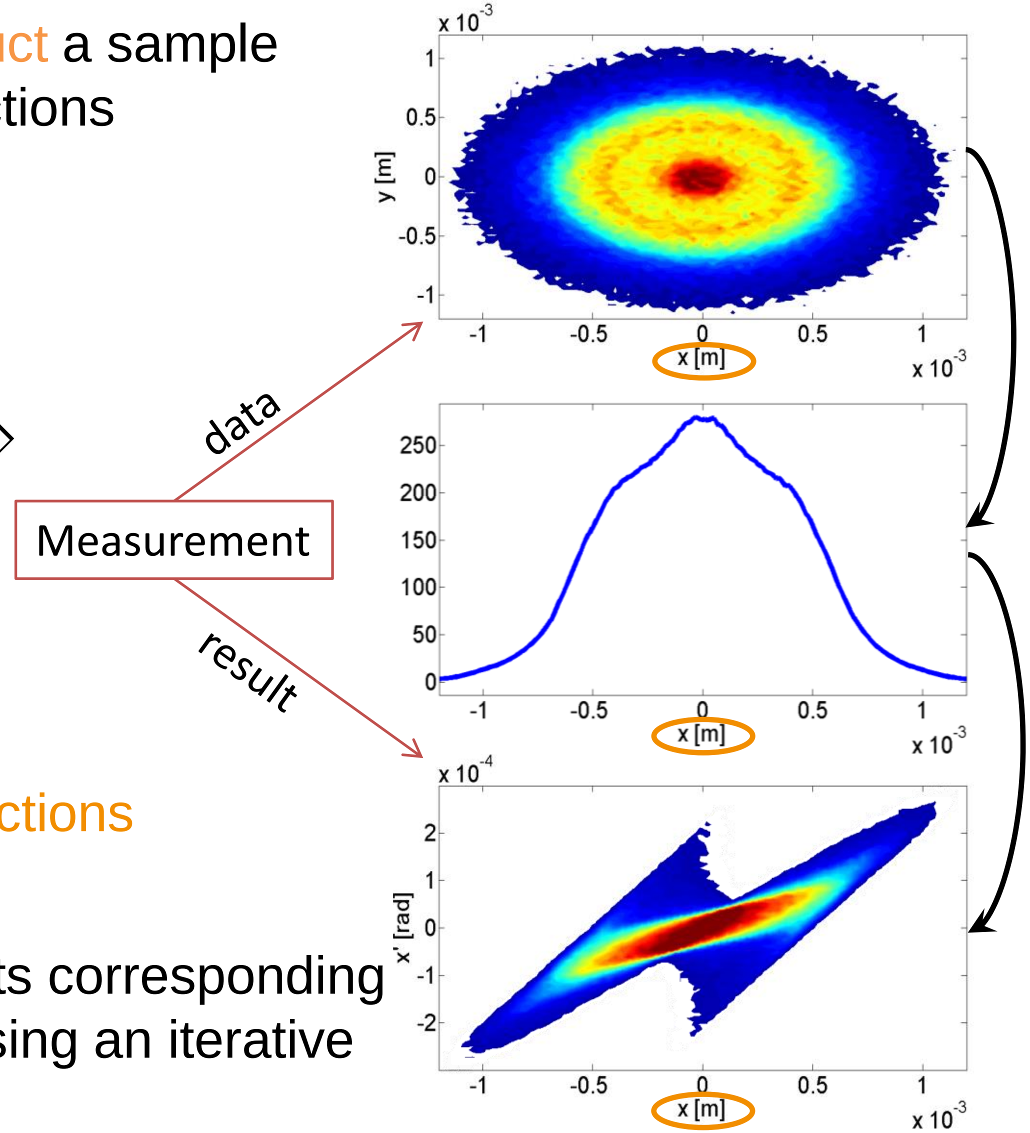
> Diagnostics for the transverse phase space: 3 slit-scan stations (EMSYs) and 1 phase space tomography [PST] module

> Various applications require transverse beam matching. Due to the constantly changing machine parameters, fast solutions are needed

Phase Space Tomography (PST)

- Principle of tomography: reconstruct a sample using its projections at different directions





- Beam diagnostics: reconstruct the transverse phase space, using projections in the real space → common axis!

- Reconstruct each projection with its corresponding transformation (→ transfer matrix) using an iterative algorithm (MENT)

Phase Space Tomography (features)

+ Improved signal-to-noise ratio

  (→ suitable for low charges, single bunch and slice measurements)

+ Simultaneous measurement of both transverse planes

  (→ less prone to short-term machine instabilities)

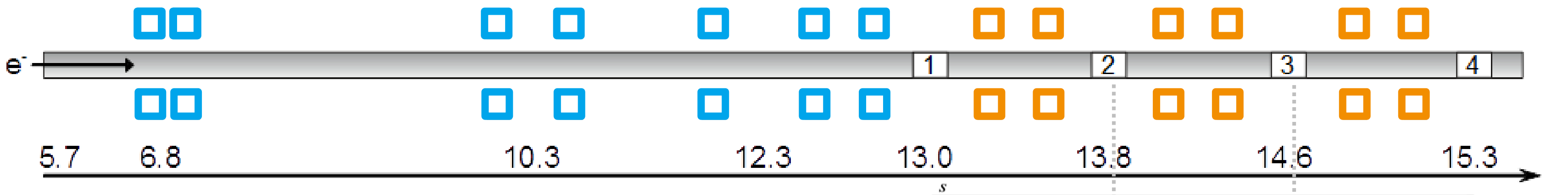
+ Quasi non-destructive measurement using fast kickers

  (→ monitoring of long term machine stability)

− Requires beam matching and space-charge treatment

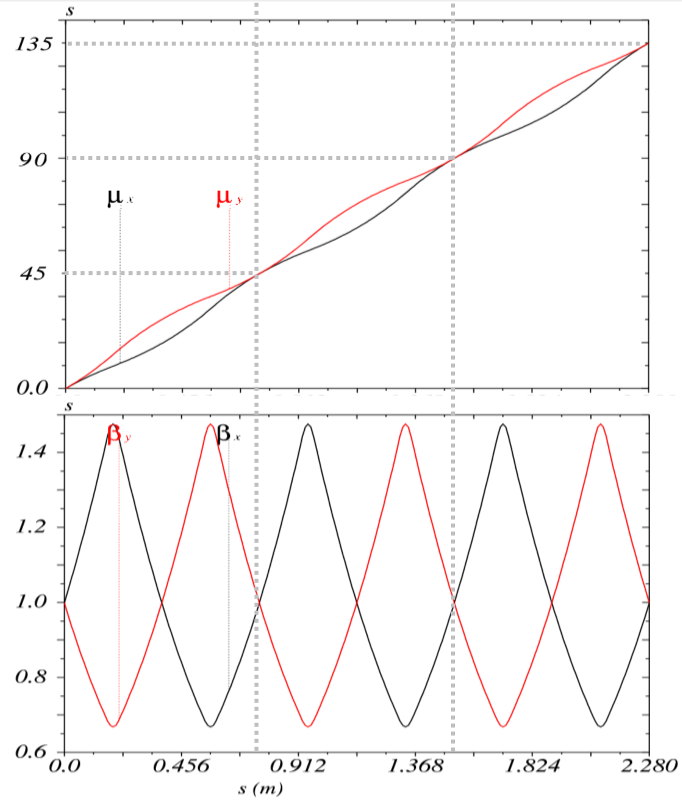
Phase Space Tomography (PITZ)

> Components:



1. FODO cells for the phase-space transformation & projection screens for data acquisition

2. Matching lattice for the necessary beam parameters in front of FODO lattice



> Matching requirements:

1. equidistant phase advance values (45°) @ each PST screen (∝ rotation angles)

2. Courant-Snyder parameters @ 1st screen→ $\beta_{x,y}$ = 1.0 m, $\alpha_{x,y}$ = ±1.1

Beam matching with space charge: periodic and dense lattices

- Under the conditions of :
  - ✓ periodic focusing
  - ✓ (fairly) constant emittance

  } FODO lattice

  the smooth-approximation theory* can be used to correlate the beam dynamics **without** and **with** space charge (linear component)

- The lattice is approximated by a uniform focusing channel which can be tuned to the matched beam solution: *R(z)* = constant, *R'(z)* = 0

- The net focusing strength (including space charge, k) is expressed as a function of the external focusing force (k_0): $k = \sqrt{{k_0}^2 - \frac{K}{R^2}}$

- Enables codes with no space-charge consideration (MAD) to perform space-charge matching by a proper scaling of the beam parameters

* Martin Reiser: Theory and Design of Charged Particle Beams, Wiley

Beam matching with space charge: periodic and dense lattices (procedure)

1. Requirements: space-charge density (emittance and generalized perveance)

2. The desired matching constrains (45º) are scaled accordingly (e.g. 55º)

3. A traditional MAD matching is performed using the scaled parameters, providing the required focusing strength

4. Reverse-scaling of the MAD tracking results to obtain the corresponding beam parameters in the presence of space charge

Beam matching with space charge: periodic and dense lattices (simulation)

Matching result of nominal PITZ beam – evaluated with ASTRA
(1 nC, 22 ps flat-top, 25 MeV/c, 1 mm·mrad)

	Phase-advance mismatch @ 2nd screen	3rd screen	4th screen
X plane			
Traditional MAD matching	-3.1°	-16.9°	-34.5°
MAD with space charge consideration	-0.9°	-0.9°	-1.2°
Y plane			
Traditional MAD matching	-4.7°	-20.2°	-37.8°
MAD with space charge consideration	-1.9°	-4.5°	-3.6°

> The phase-advance mismatch is reduced from 38° to 5° (depending on space-charge density)

> Method yields almost instant results

Beam matching with space charge: aperiodic and sparse lattices

> Matching section: neither periodic nor constant emittance along it

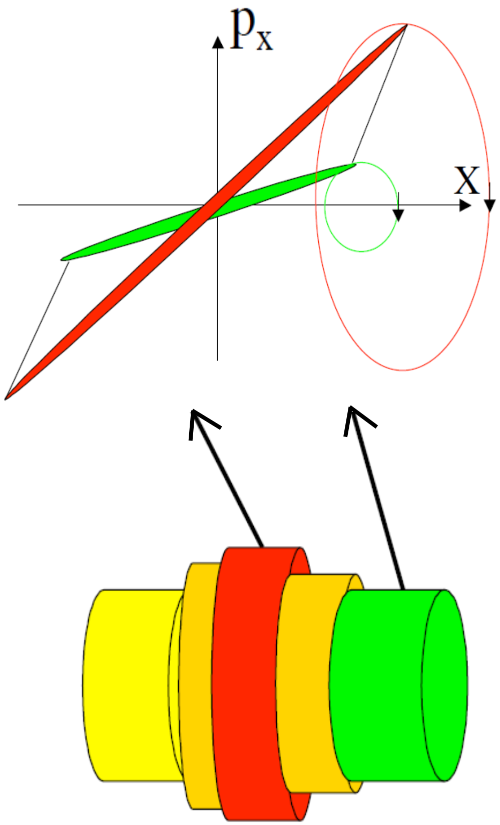
> Except from defocusing, space charge also induces correlated emittance growth

> Different longitudinal slices obtain different transverse parameters, overlapping in the phase space

> In order to match the target values all along the bunch, the slices have to be aligned

> The matching procedure needs to additionally perform emittance compensation using quadrupoles

Image courtesy: M. Ferrario



Beam matching with space charge: aperiodic and sparse lattices (SC code)

> Solution: SC software (HZB – A. Matveenko)

> Tracking functionality: includes linear space-charge forces for each slice → correlated emittance growth considered + immediate result

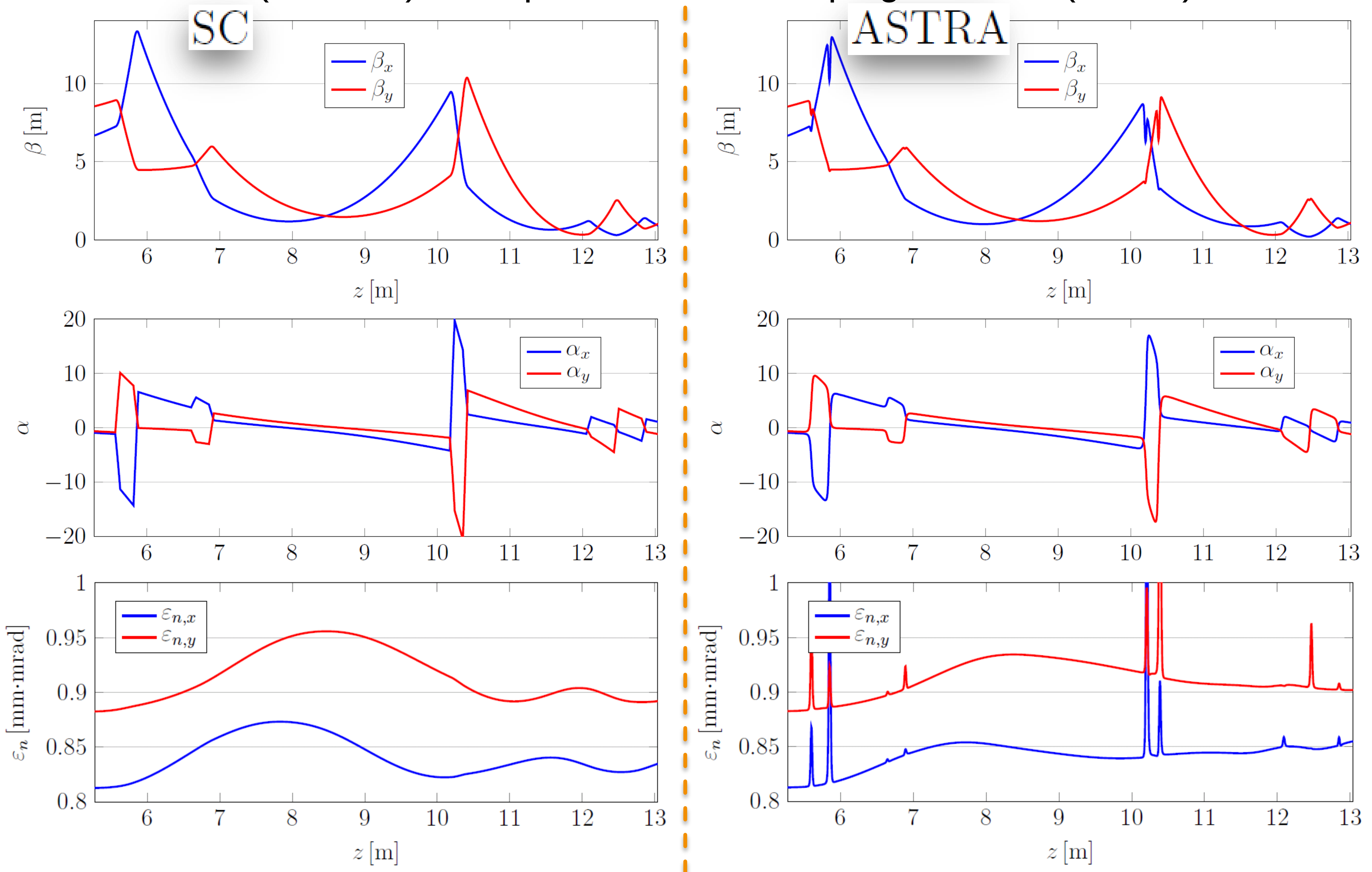
> Matching functionality: iterative tracking with varying quadrupole strengths in search for a goal projected emittance

> Adjusted to the needs of PITZ:

- β- and α-parameters as additional matching constraints
- on-line feature for measurements:
  slice rms moments as input (apart from an ASTRA distribution)

Beam matching with space charge: aperiodic and sparse lattices (simulation)

(~15 min) / 500 pC, 21 MeV/c, 12 ps gaussian \ (~3.5 h)



Beam matching with space charge: aperiodic and sparse lattices (measurement)

	+1.8 m (4 quads): slit-scan			+7.8 m (9 quads): tomography		
	SC	ASTRA	Measured	SC	ASTRA	Measured
β_x [m]	2.08	1.99	2.83 ± 0.11	0.91	1.01	0.78 ± 0.02
α_x	1.09	1.16	1.42 ± 0.10	1.13	0.96	0.70 ± 0.02
ε_x [mm·mrad]	0.86	0.85	0.94 ± 0.04	0.83	0.85	**1.96** ± 0.03
β_y [m]	4.83	4.80	5.51 ± 0.37	1.03	1.10	1.07 ± 0.01
α_y	2.29	2.39	3.13 ± 0.14	-1.12	-1.15	-1.09 ± 0.02
ε_y [mm·mrad]	0.92	0.91	1.25 ± 0.07	0.89	0.90	**1.44** ± 0.02

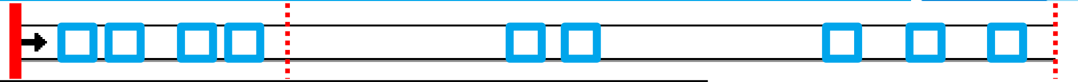
> Acceptable agreement between simulated and measured Courant-Snyder parameters (mismatch of several hundreds % when space charge is neglected)

> Increased emittance due to measurement imperfections?

1. machine and operational imperfections (RF, laser, trajectory, …)
2. used model: input distribution, non-linear fields, transverse coupling
3. beam halo: grows downstream + is better resolved at PST than at EMSYs

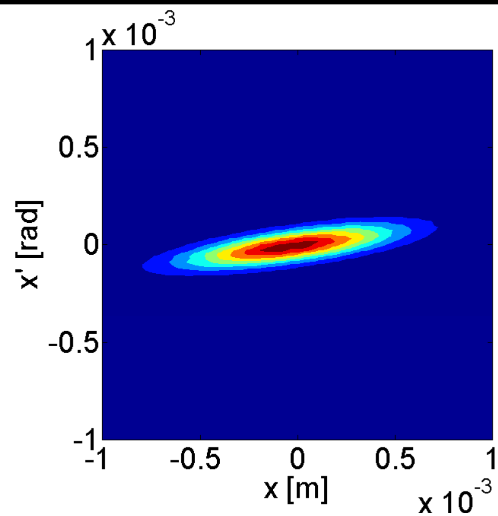
Beam matching with space charge: aperiodic and sparse lattices (measurement)

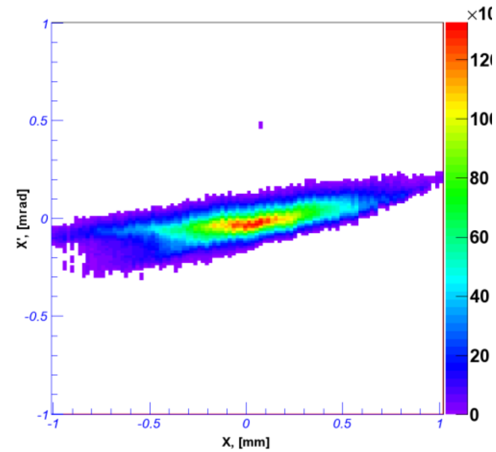
Beginning of matching [slit scan] :



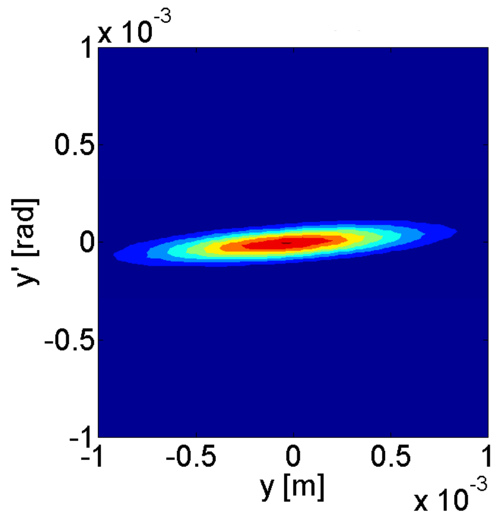
ASTRA	Measured

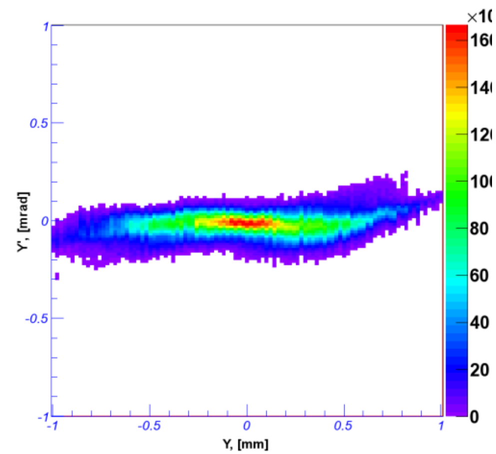
X





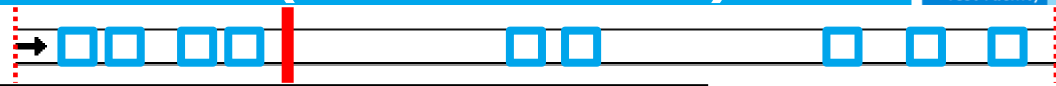
Y





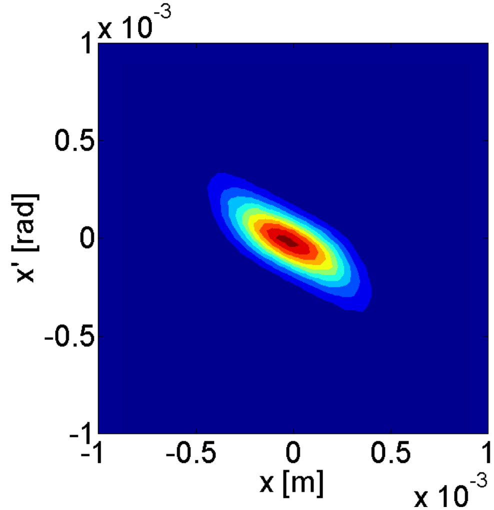
Beam matching with space charge: aperiodic and sparse lattices (measurement)

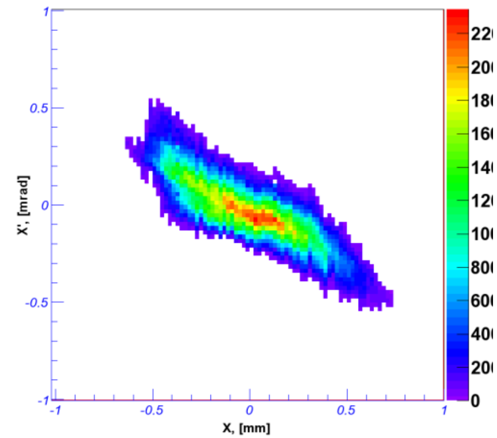
1.8 m downstream [slit scan] :



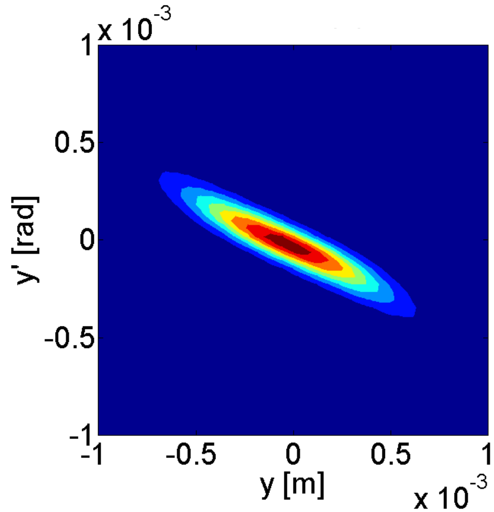
ASTRA	Measured

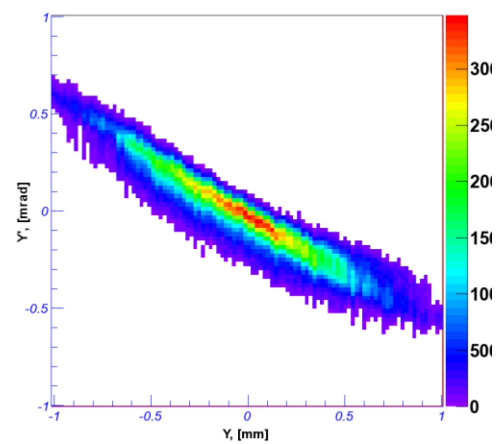
X





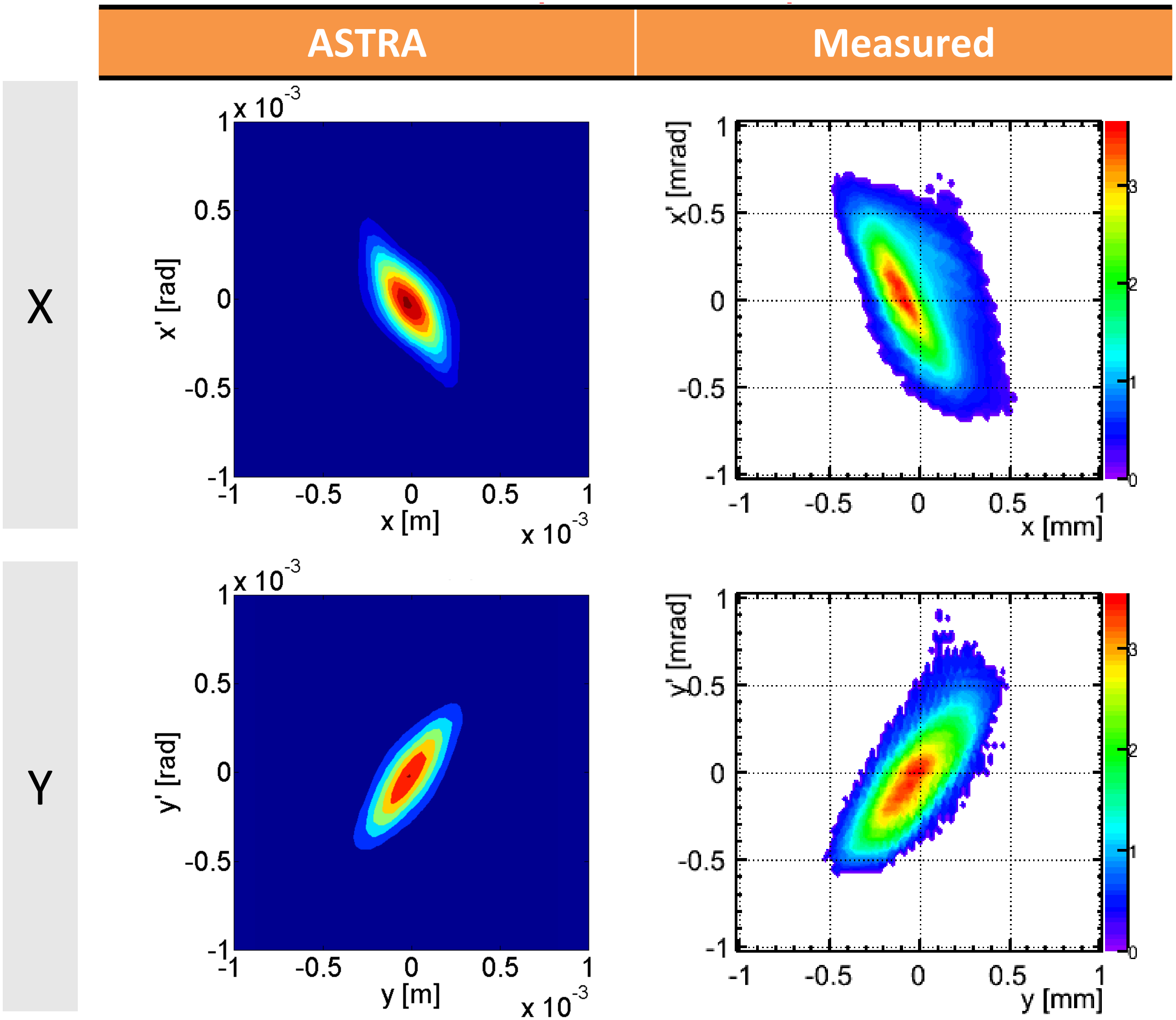
Y





Beam matching with space charge: aperiodic and sparse lattices (measurement)

7.8 m downstream [tomography] :



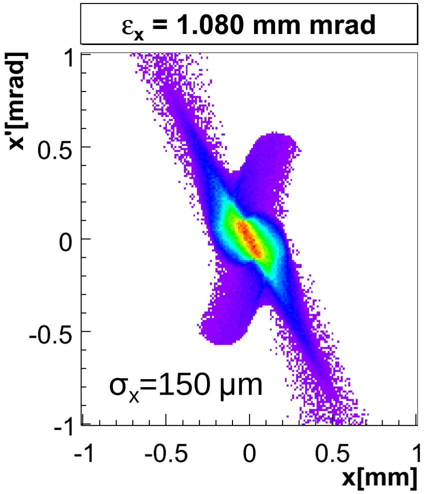
Space charge in the tomographic reconstruction

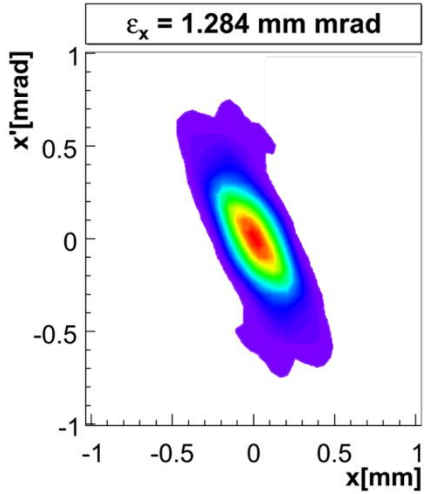
- The reconstruction of the captured projections requires an accurate description of the phase-space transformations
- Defocusing of space charge has to be included in the transfer matrices

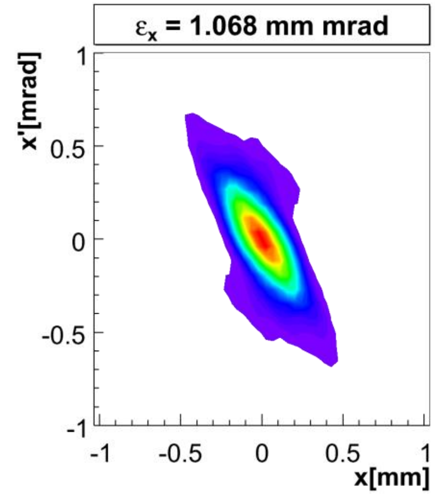
- Perform a linear space-charge tracking (SC) along the FODO lattice, using an estimation for the entering beam parameters
- Calculate corresponding transfer matrices from the simulation result (Courant-Snyder parameters at the projection screens) using:

$$M_q = \begin{pmatrix} \sqrt{\frac{\beta_{qf}}{\beta_{qi}}}(cos\phi_q + \alpha_{qi} sin\phi_q) & \sqrt{\beta_{qf}\beta_{qi}} sin\phi_q \\ -\frac{1+\alpha_{qf}\alpha_{qi}}{\sqrt{\beta_{qf}\beta_{qi}}}\sin\phi_q + \frac{\alpha_{qi}-\alpha_{qf}}{\sqrt{\beta_{qf}\beta_{qi}}}\cos\phi_q & \sqrt{\frac{\beta_{qi}}{\beta_{qf}}}(cos\phi_q - \alpha_{qf} sin\phi_q) \end{pmatrix}$$

Space charge in the tomographic reconstruction (ASTRA simulation: 1 nC, 22 ps flat-top, 25 MeV/c)







+19%

-1%

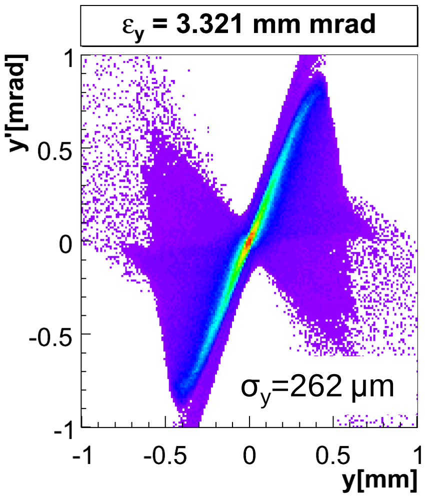
Original distribution

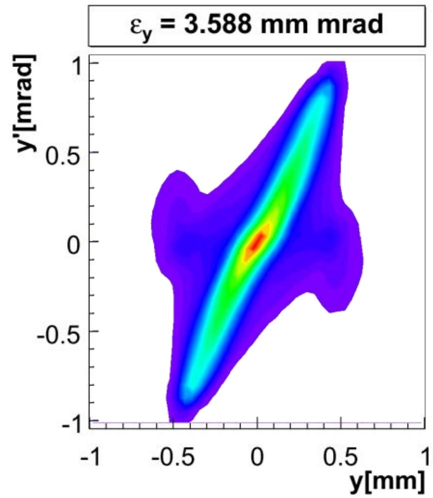
No space charge

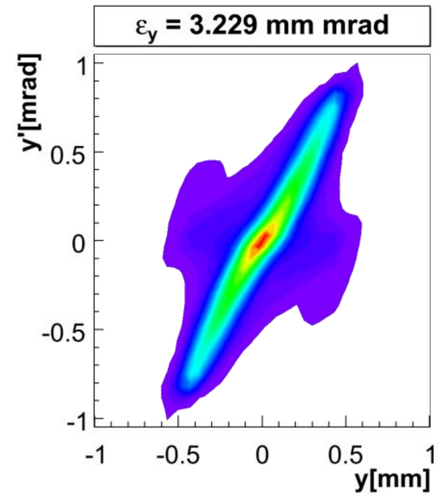
Linear space charge

+8%

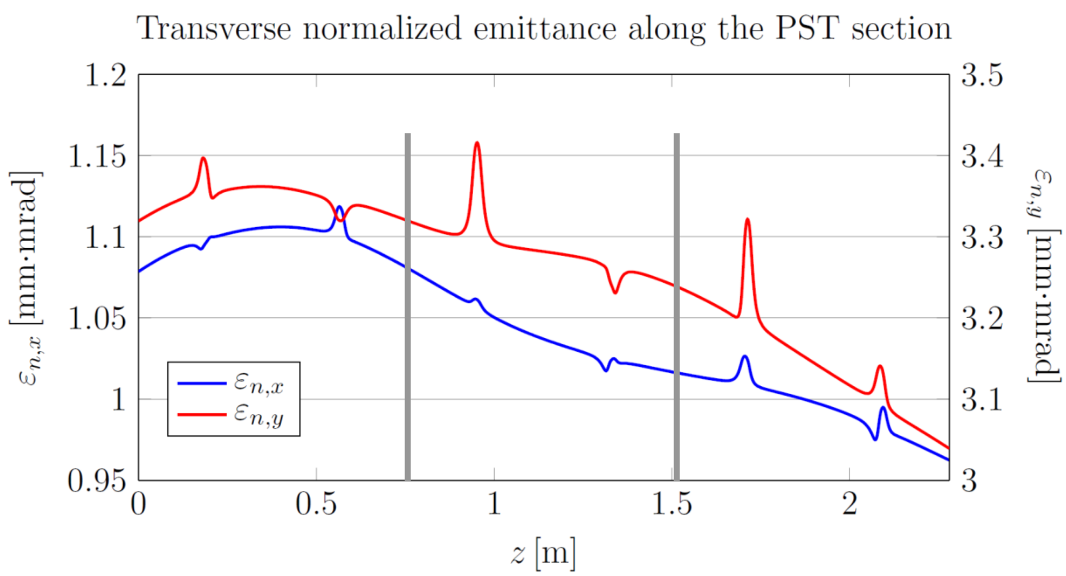
-3%







Space charge in the tomographic reconstruction (ASTRA simulation: 1 nC, 22 ps flat-top, 25 MeV/c)



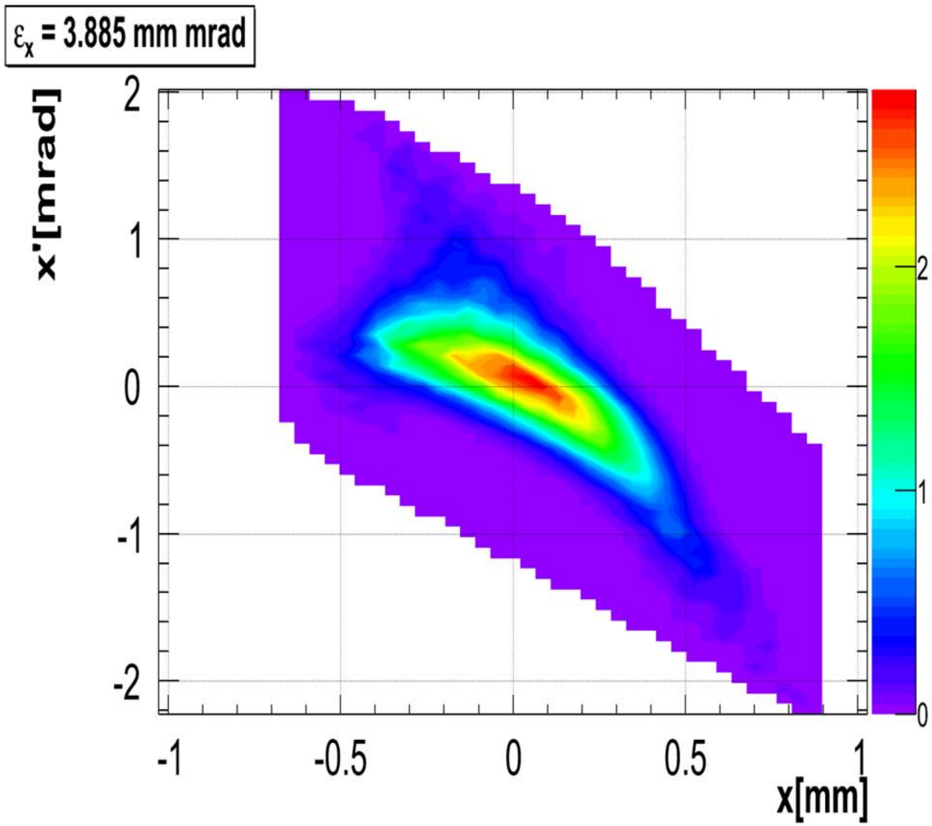
> With respect to the mean of the projected emittance…

	X-plane	Y-plane
No space charge reconstruction	+24%	+11%
Linear space charge reconstruction	+3%	0%

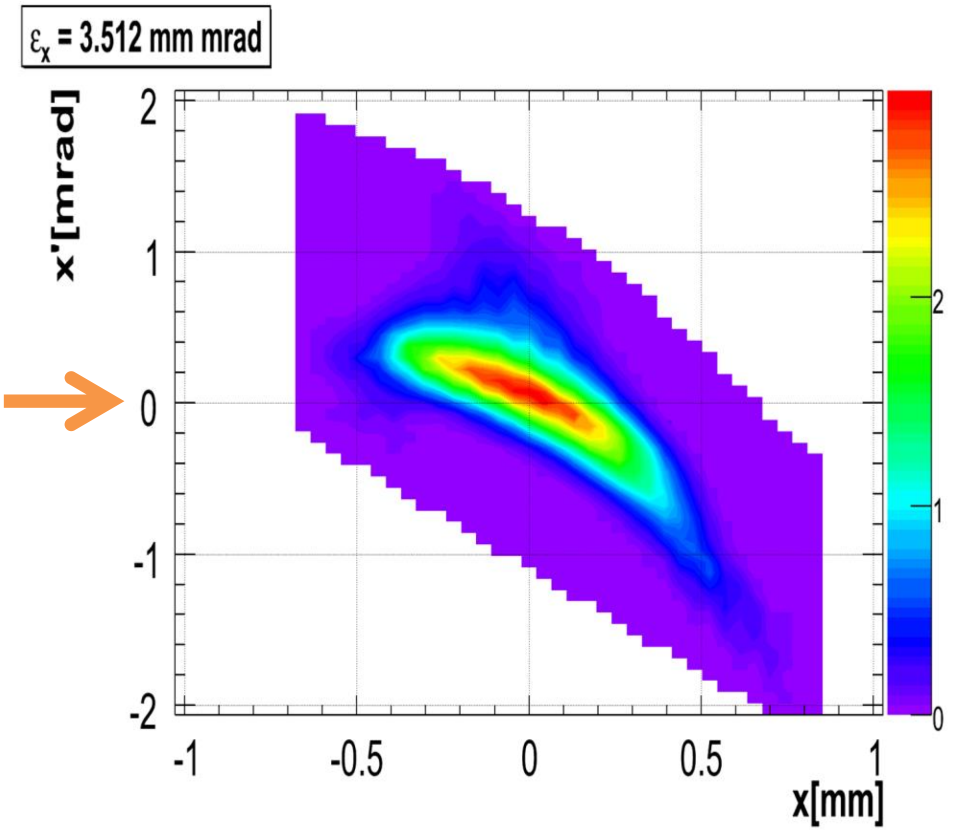
~ 20% error reduction with the linear space-charge correction

Space charge in the tomographic reconstruction (measurement: 1 nC, 22 ps flat-top, 25 MeV/c)

> Without space charge



> With space charge



Reduction in the calculated emittance = 11%
(transverse rms size ~ 0.25 mm)

Space charge in the tomographic reconstruction (and beyond…)

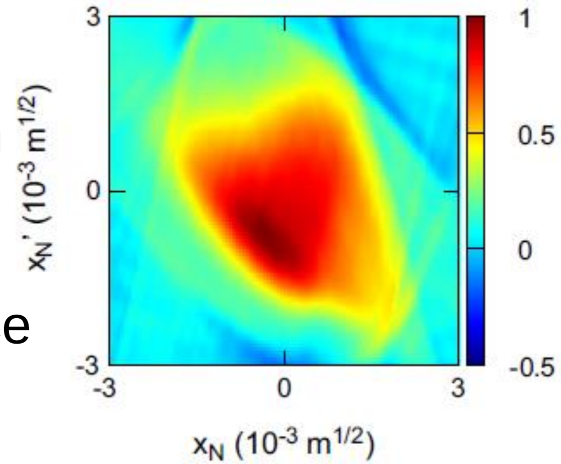
- Method can be applied to various measurement techniques and beam parameters [current, dimensions, energy]

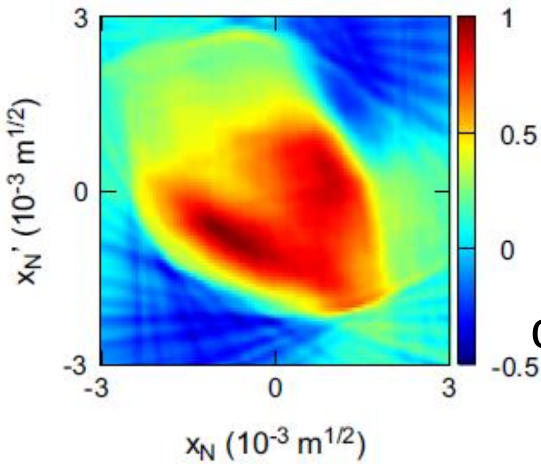
- Multiscreen measurement at bunch compressor exits of FELs: comparable results expected (similar space-charge forces)
  - XFEL: 20 pC @ BC 2 [4 kA, 20 μm, 2.4 GeV]
  - FLASH: 20 pC @ BC 3 [1.5 kA, 65 μm, 450 MeV]

from desy.de/fel-beam

- Quad-scan tomography at ALICE (Cockroft Institute) [80 pC, 12 ps, 12 MeV]: space-charge treatment explained measurement discrepancies

Short drift
reconstruction
||
small space charge influence





Long drift
reconstruction
||
big space charge influence

Summary and outlook

- The major effect of space charge is included in the transverse matching and the phase space tomography at PITZ:

1. Two matching strategies for different types of lattices:
   - instant solution for periodic lattices (→ MAD + smooth approximation)
   - quick solution for irregular lattices (→ SC)

   Both solutions yield good results in the most time-efficient way
2. The tomographic reconstruction is corrected by ~ 20%

- Results applicable to FELs in matching and multiscreen measurements at high energies and compressed dimensions (bunch compressor exits)

- Outlook: evaluate the effect of halo in the matching efficiency of SC, test alternative matching tools (e.g. Xtrack, DESY, M. Dohlus)
- Commission fast kickers for quasi non-destructive emittance measurements, extend analysis to 4D transverse phase space

Thanks to:

PITZ group: every single member and especially Mikhail Krasilnikov, Grygorii Vashchenko, Frank Stephan

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THANK YOU.

HELMHOLTZ | ASSOCIATION

DESY

PITZ Photo Injector Test Facility Zeuthen

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