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

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DESY

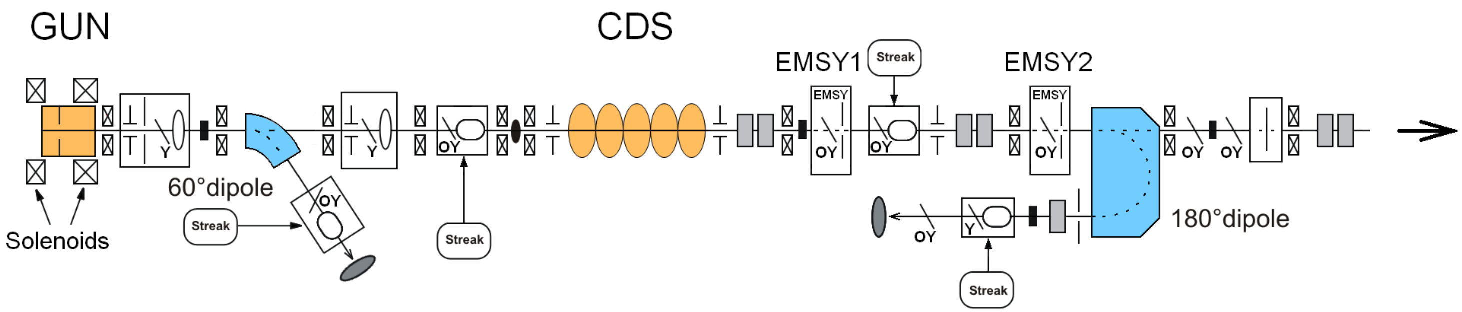
Outline

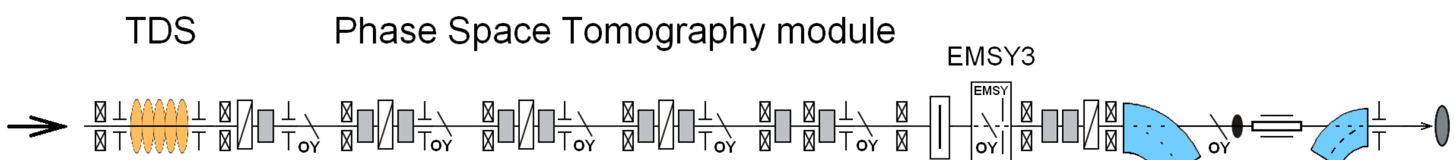
- Basic concepts and motivation:
  - Space charge
  - PITZ facility
  - Transverse phase space tomography (PST)
- Beam matching with space charge: periodic and dense lattices
- Beam matching with space charge: aperiodic and long lattices
- Space charge in the tomographic reconstruction
- Summary and outlook

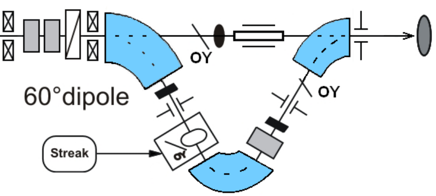
Space charge

- Coulomb repulsion among the particles of the beam
- Electromagnetic fields (only direct considered, no image fields) from a uniform cylindrical bunch to each particle:
  - $E_r(r,\zeta) = \frac{Ir}{2\pi\epsilon_0 R^2 \beta_{rel} c} g(\zeta)$:
    - 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

Photo Injector Test facility at DESY, Zeuthen site



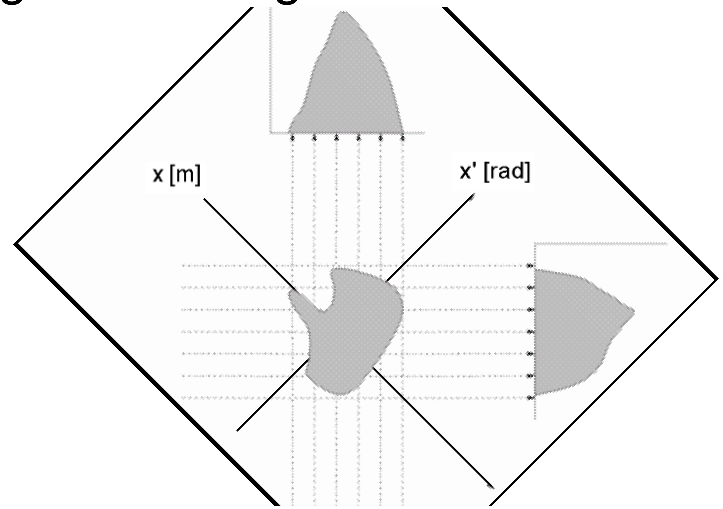


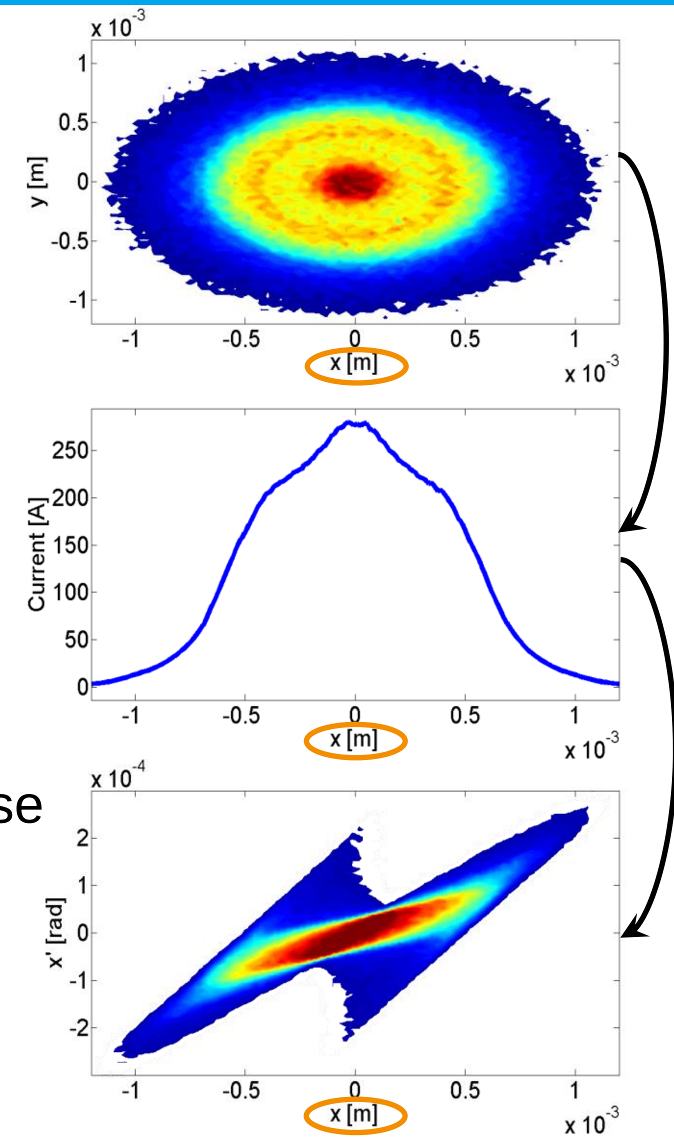


- Electron bunches with high space-charge influence
  - < 25 ps laser pulses
  - 20 pC - 1 nC bunch charge
  - < 25 MeV/c momentum
- Diagnostics for the transverse phase space: 3 slit-scan stations (EMSYs) and 1 phase space tomography [PST] module
- Various applications require transverse beam matching. Due to the constantly changing machine parameters, fast solutions are needed

Transverse Phase Space Tomography (PST)

> Principle of tomography: reconstruct a sample using its projections at different directions ↔ fixed projection plane while sample rotates (undergoes linear geometrical transformations)





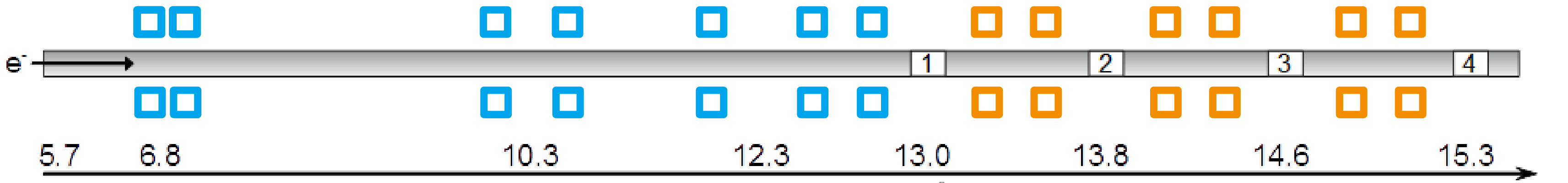
> Beam diagnostics: reconstruction of the transverse phase space → use the beam's spatial projections (common between the real and the phase space)

> Reconstruct the projections with an iterative algorithm (MENT) using the corresponding phase space transformations (→ transfer matrices)

Transverse Phase Space Tomography (features)

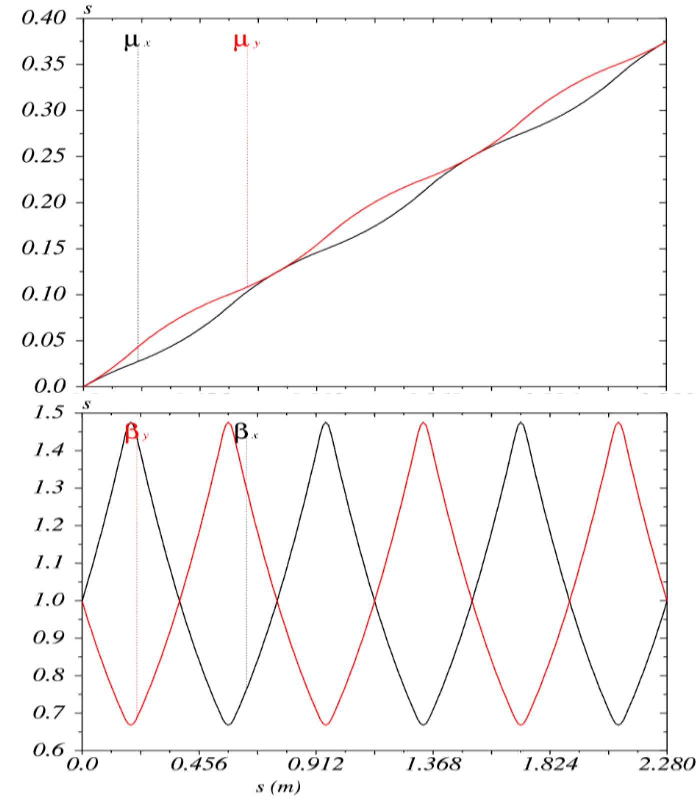
- \+ Improved signal-to-noise ratio (→ suitable for low charges, single bunch measurements)
- \+ Simultaneous measurement of both transverse planes + fast data acquisition (→ less prone to short-term machine instabilities)
- \+ Quasi non-destructive measurement using fast kickers (→ monitoring of the long term machine instability)
- − Requires beam matching and space-charge treatment

> Components:



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

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



> Matching requirements:

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

2. Twiss 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)* = *R* = 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 used 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 a beam with 1 nC, 22 ps flat-top, 25 MeV/c, 1 mm·mrad evaluated with ASTRA

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

- The phase-advance mismatch is reduced from 38° to 5°
- Method yields almost instant results

Beam matching with space charge: aperiodic and long lattices

> Matching section: neither periodic nor constant emittance along it

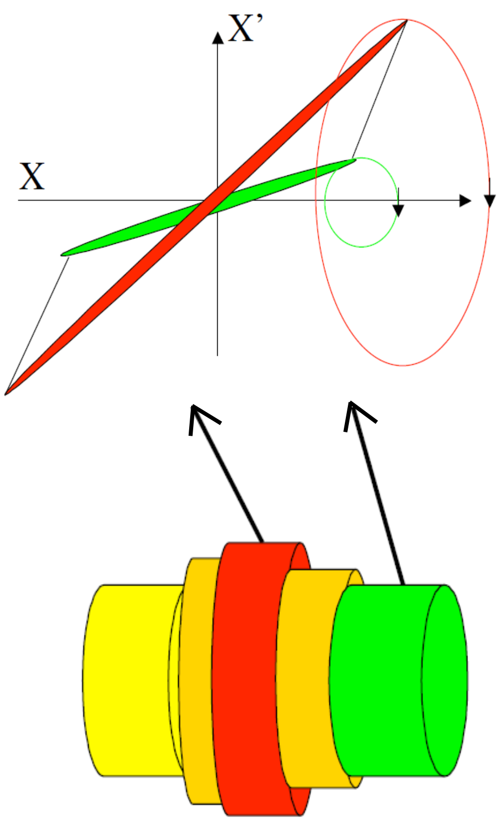
> Except from defocusing, space charge also induces correlated emittance growth

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

> In order to match the target values all along the bunch, the emittance oscillations have to be suppressed

> A matching procedure is needed which additionally performs emittance compensation on elliptical beams using quadrupoles

Image courtesy: M. Ferrario



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

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

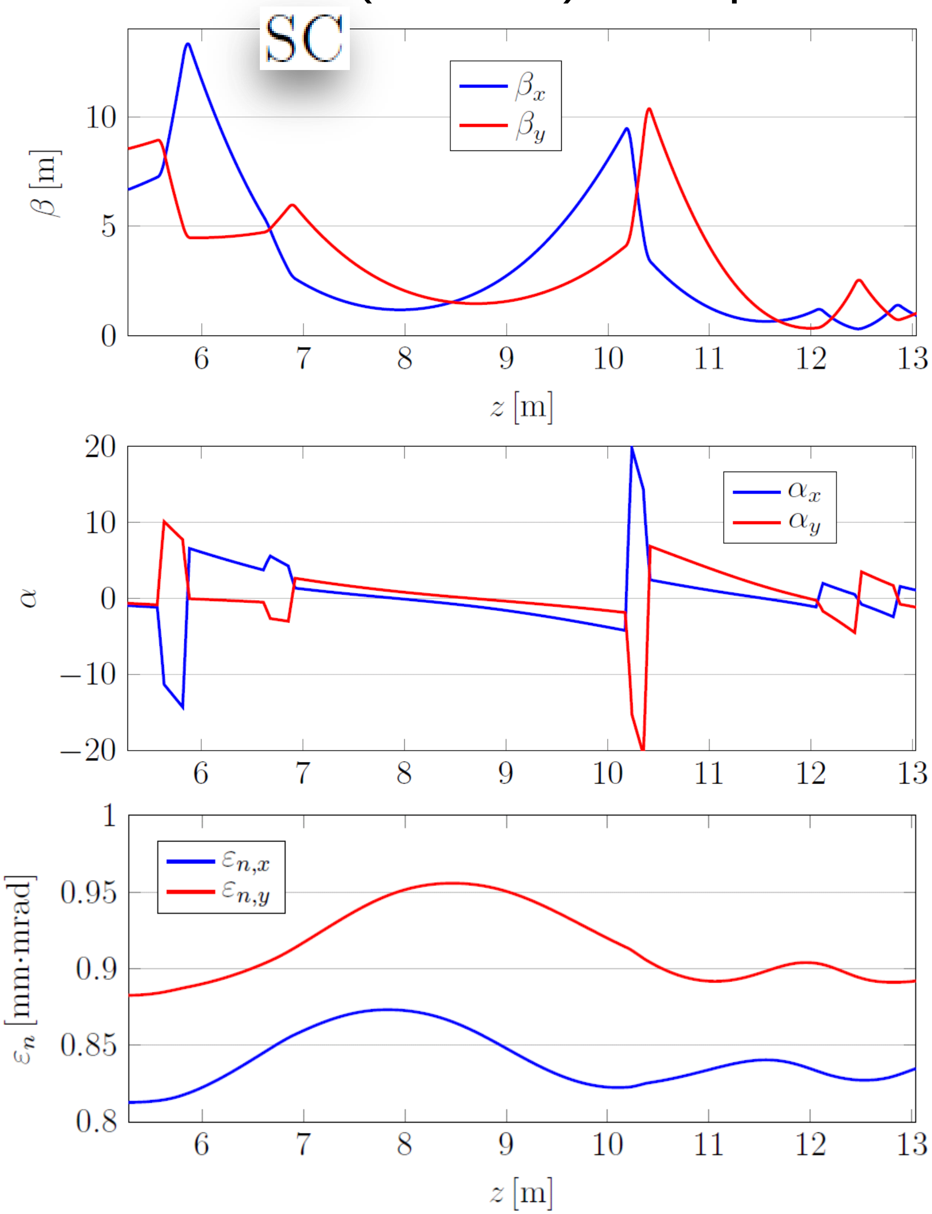
- Tracking functionality: includes linear space-charge forces for each slice → correlated emittance growth considered + immediate result

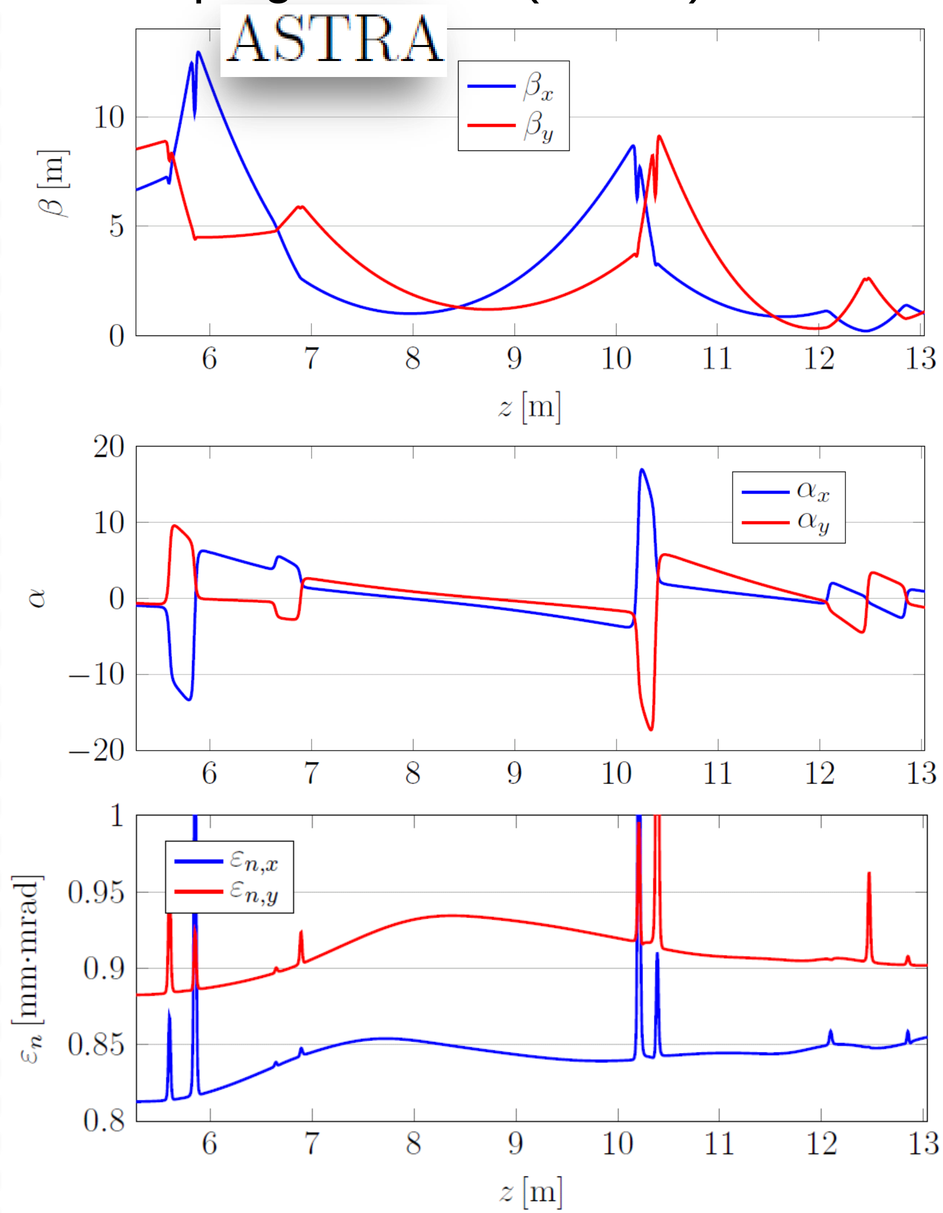
- Matching functionality: iterative tracking with varying quadrupole strengths in search for a goal projected emittance → crucial for matching efficiency

- Adjusted to the matching needs of PITZ:
  - β- and α-parameters as additional matching constrains
  - on-line application during measurements: slice rms moments as input (apart from an ASTRA distribution)

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

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





Beam matching with space charge: aperiodic and long lattices (simulation + measurement)

	1.8 m downstream (4 quads)			7.8 m downstream (9 quads)		
	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

> Good accordance between simulated and measured Twiss parameters (mismatch of several hundreds % when space charge is neglected)

> Increased emittance due to measurement imperfections?

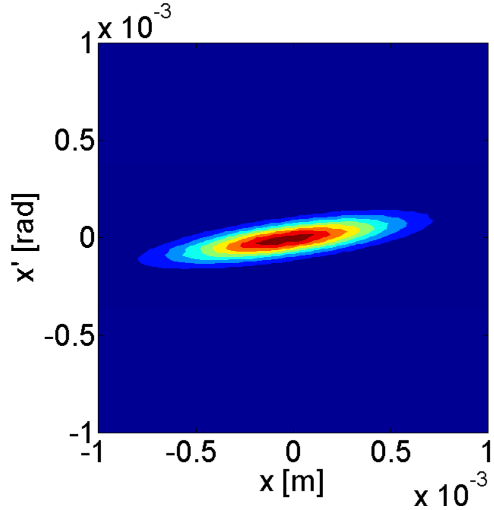
1. machine and operational imperfections (cooling, laser, jitter, trajectory, …)
2. used model: input distribution, non-linear fields, transverse coupling (coupler kick), …
3. beam halo: grows downstream + is better captured at PST than at EMSYs

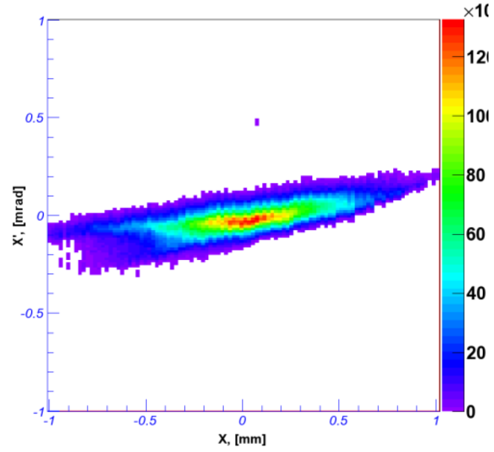
Beam matching with space charge: aperiodic and long lattices (simulation + measurement)

Beginning of matching (slit scan)

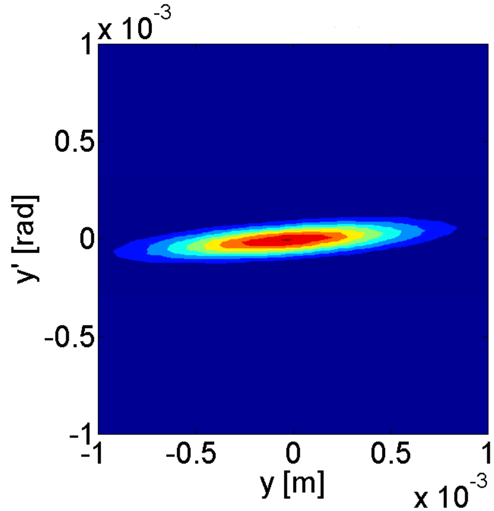
ASTRA	Measured

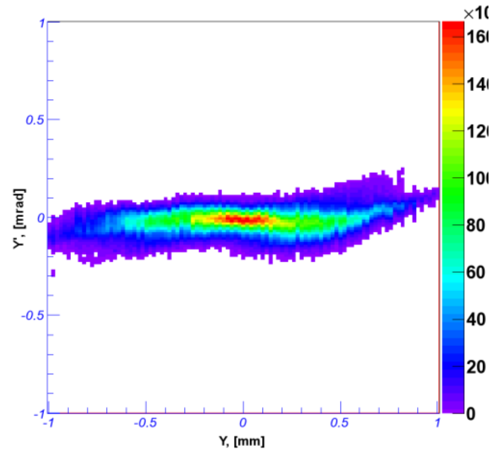
X





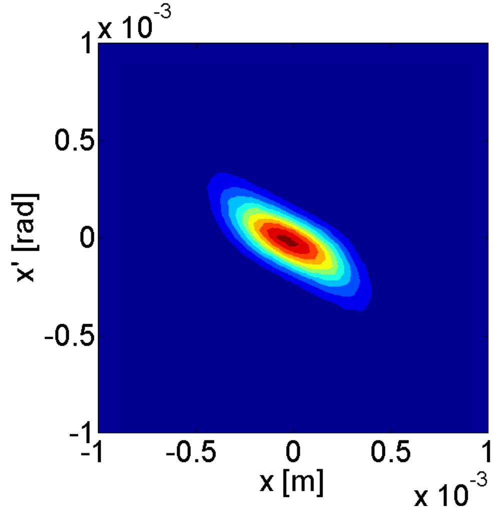
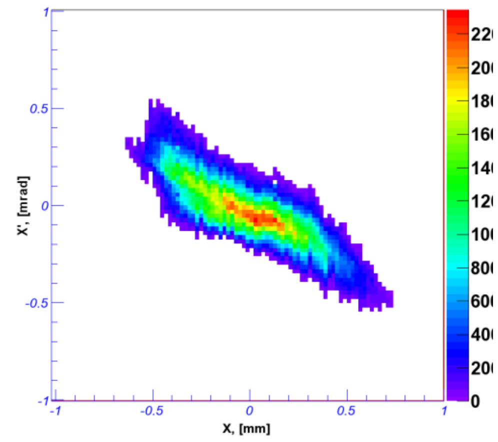
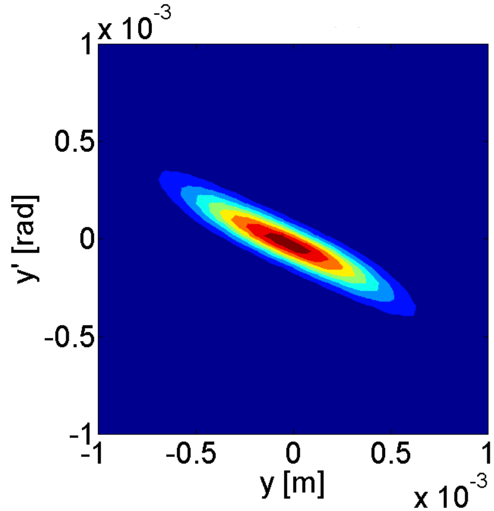
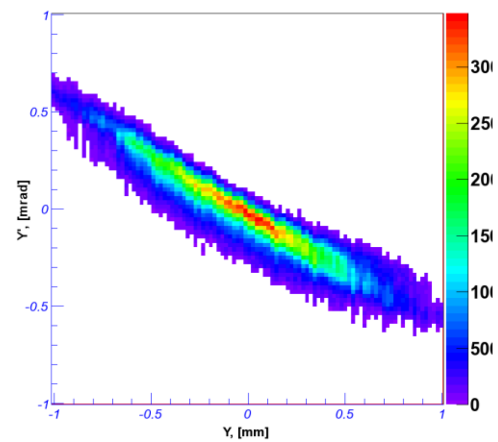
Y





Beam matching with space charge: aperiodic and long lattices (simulation + measurement)

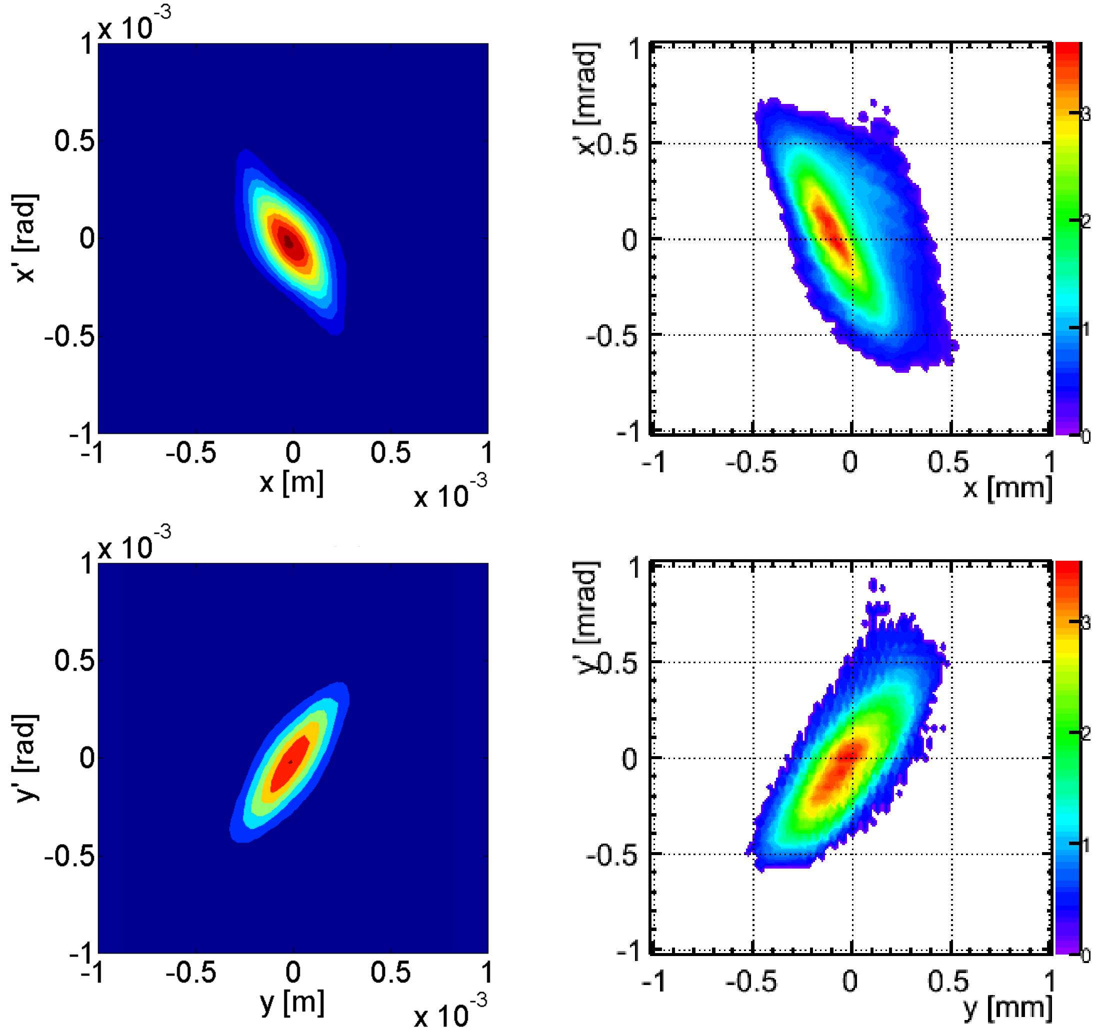
1.8 m downstream, 4 quads in between (slit scan)

	ASTRA	Measured
X		
Y		

Beam matching with space charge: aperiodic and long lattices (simulation + measurement)

7.8 m downstream, 9 quads in between (tomography)

	ASTRA	Measured
X		
Y		



Space charge in the tomographic reconstruction

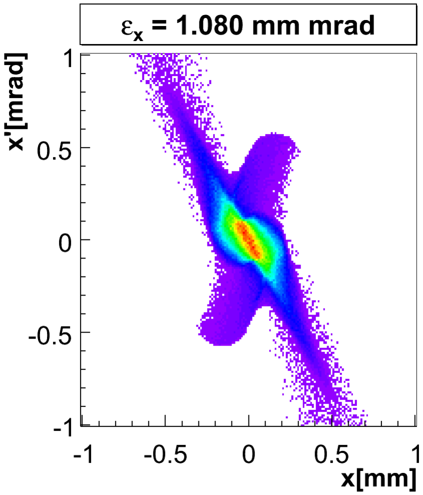
- The reconstruction of the captured projections requires an accurate description of the phase space transformations
- The defocusing effect of space charge has to be included in the transfer matrices

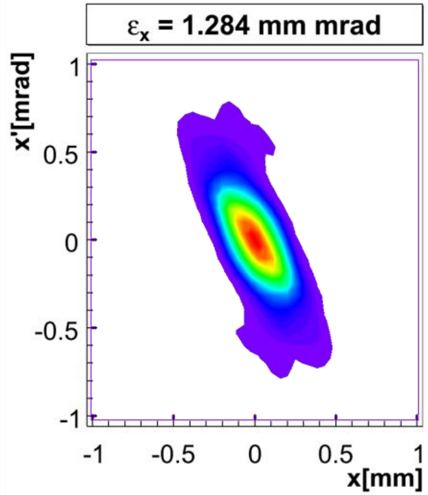
- A linear space-charge tracking of the FODO lattice is performed (e.g. SC), using an estimation for the entering beam parameters*
- From the simulated Twiss parameters at the projection screens, the corresponding transfer matrices can be calculated by:

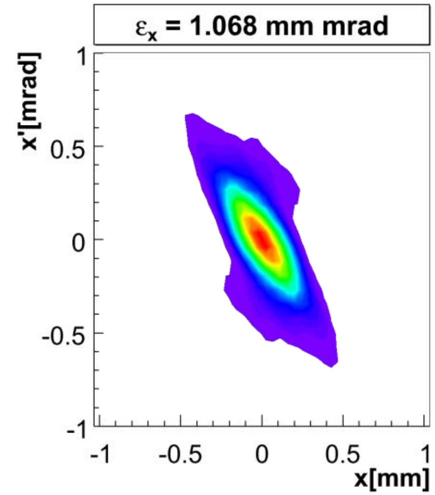
$$M_q = \begin{pmatrix} \sqrt{\frac{\beta_{qf}}{\beta_{qi}}}(cos\phi_q + \alpha_{qi} sin\phi_q) & \sqrt{\beta_{qf}\beta_{qi}} sin\phi_q \\ -\frac{1+\alpha_{qf}\alpha_{qi}}{\sqrt{\beta_{qf}\beta_{qi}}}\sin\phi_q + \frac{\alpha_{qi}-\alpha_{qf}}{\sqrt{\beta_{qf}\beta_{qi}}}\cos\phi_q & \sqrt{\frac{\beta_{qi}}{\beta_{qf}}}(cos\phi_q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

*simulation, PST/multiscreen measurement without space charge

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



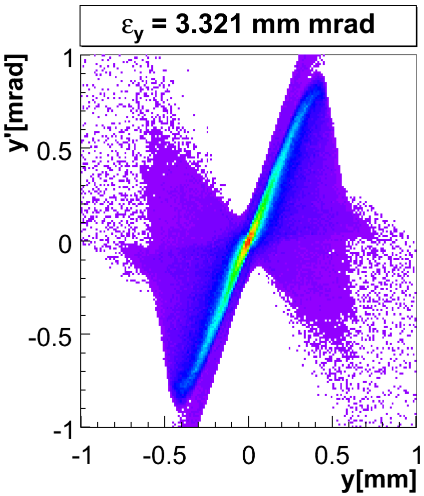


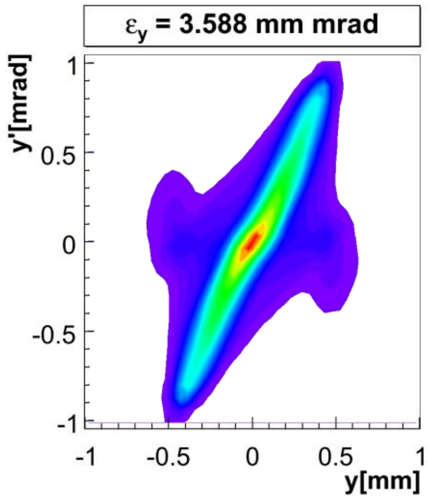


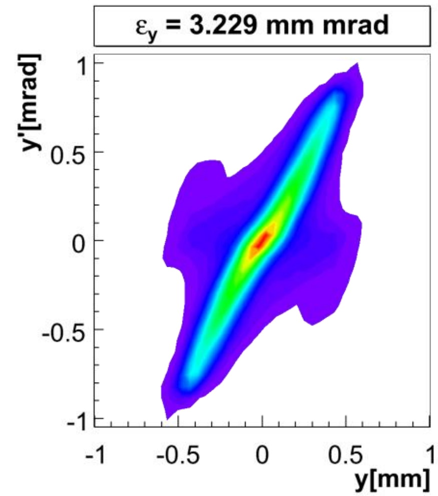
(σ_x=150 mm)
Original distribution
(σ_y= 262 mm)

+19%
No space charge
+8%

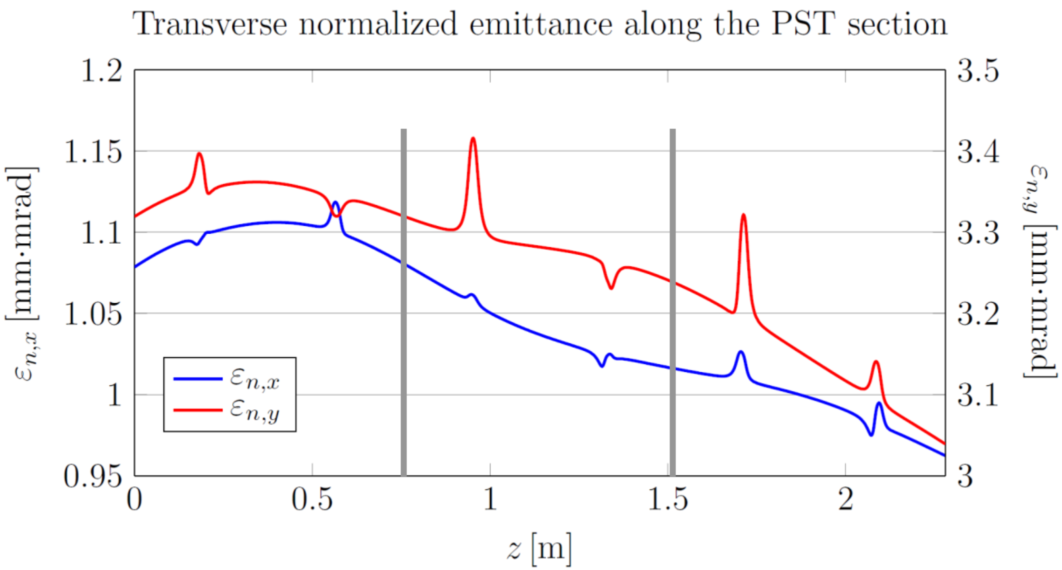
-1%
Linear space charge
-3%







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



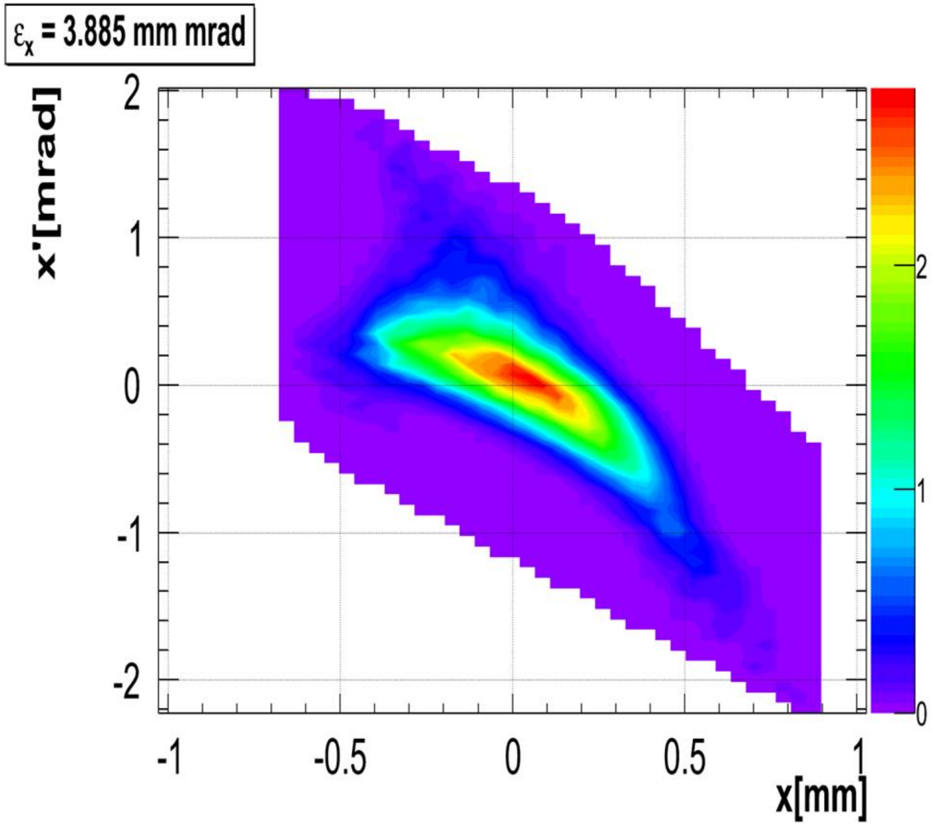
	X-plane	Y-plane
Original distribution	1.0	3.2
No space charge reconstruction	1.3 (+24%)	3.6 (+11%)
Linear space charge reconstruction	1.1 (+3%)	3.2 (0%)

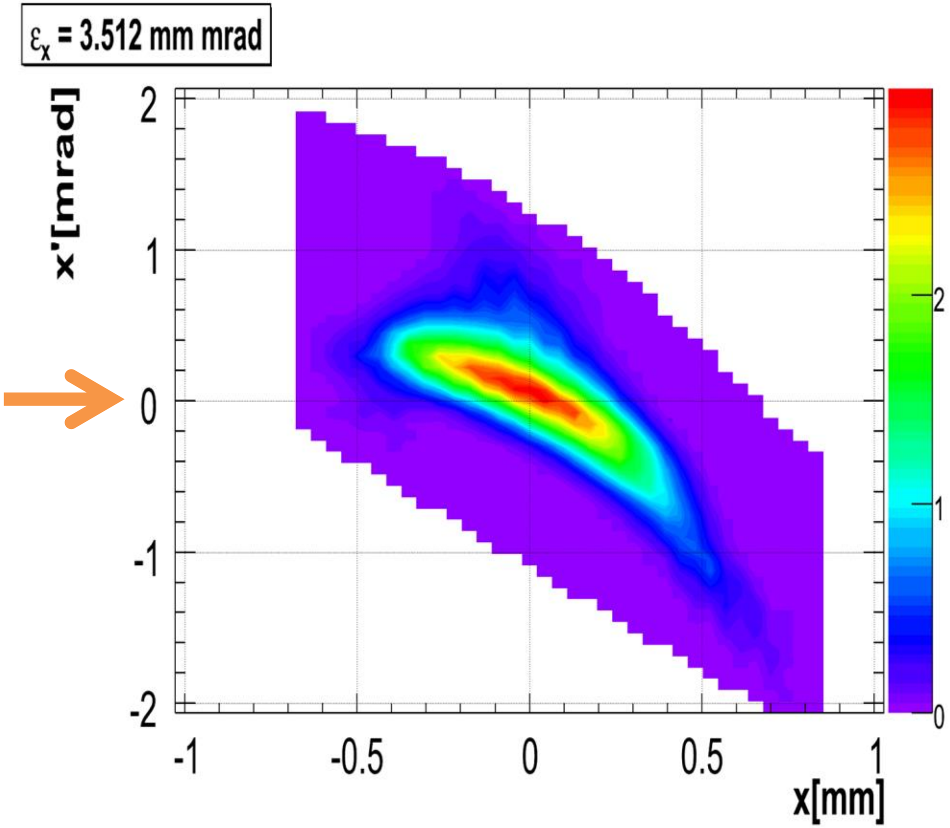
> The space-charge reconstruction reduces the error by more than 20%

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

> Without space charge

> With space charge



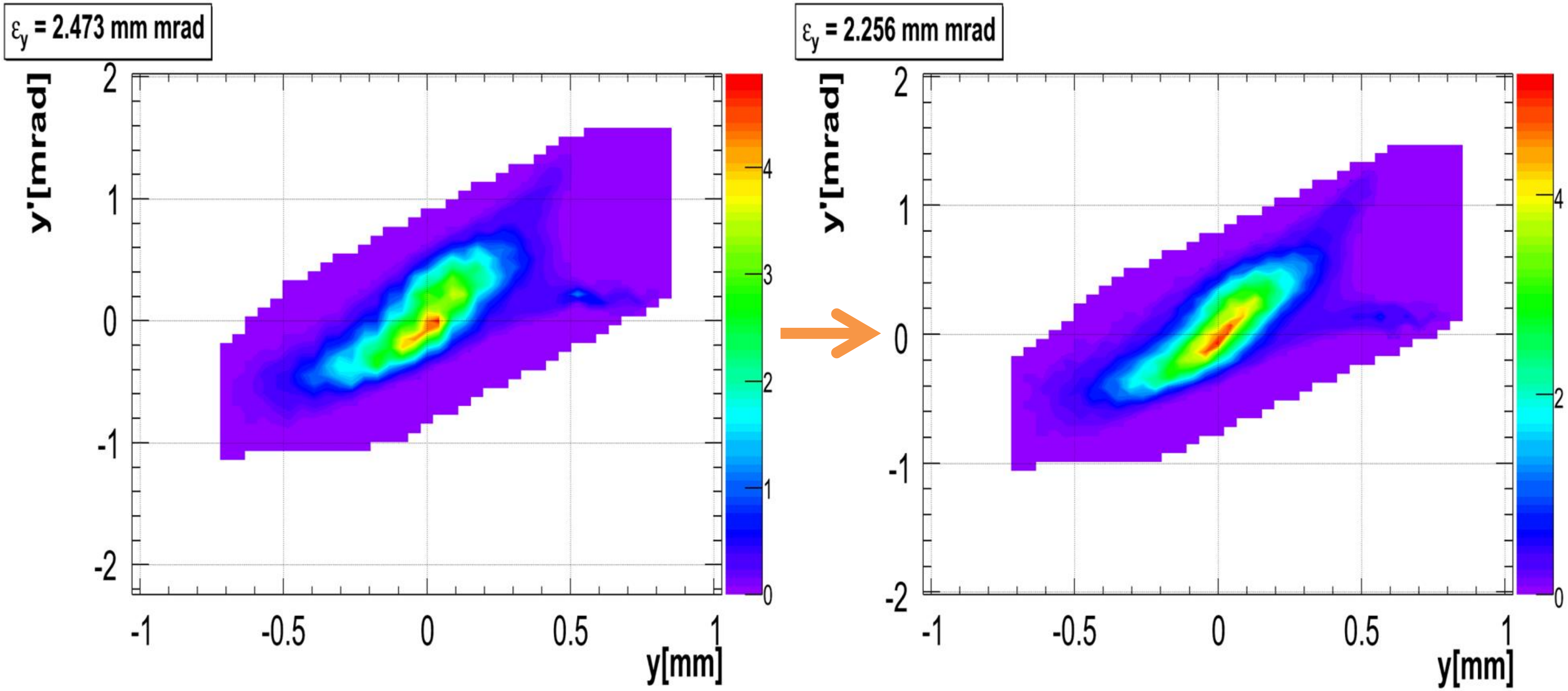


Reduction in the calculated emittance = 11%
(transverse rms size ~ 0.25 mm)

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

> Without space charge

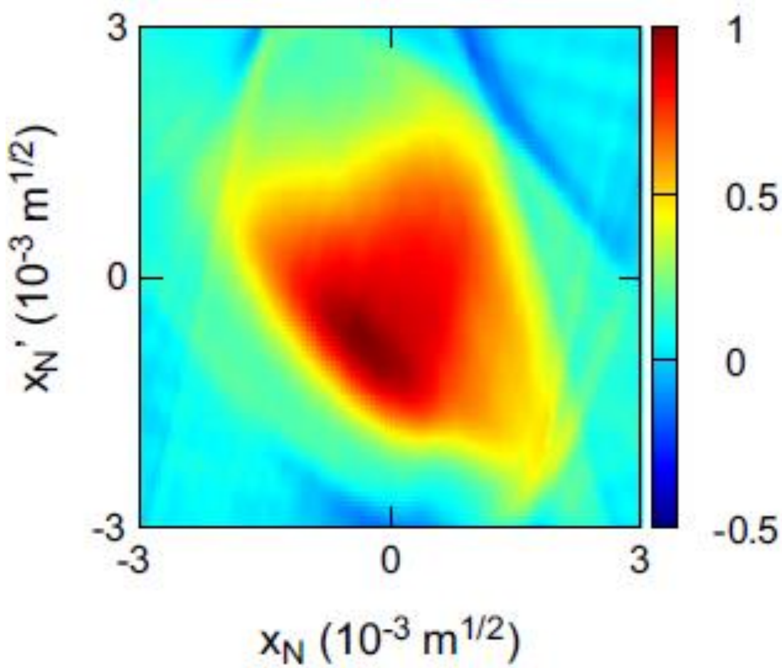
> With space charge

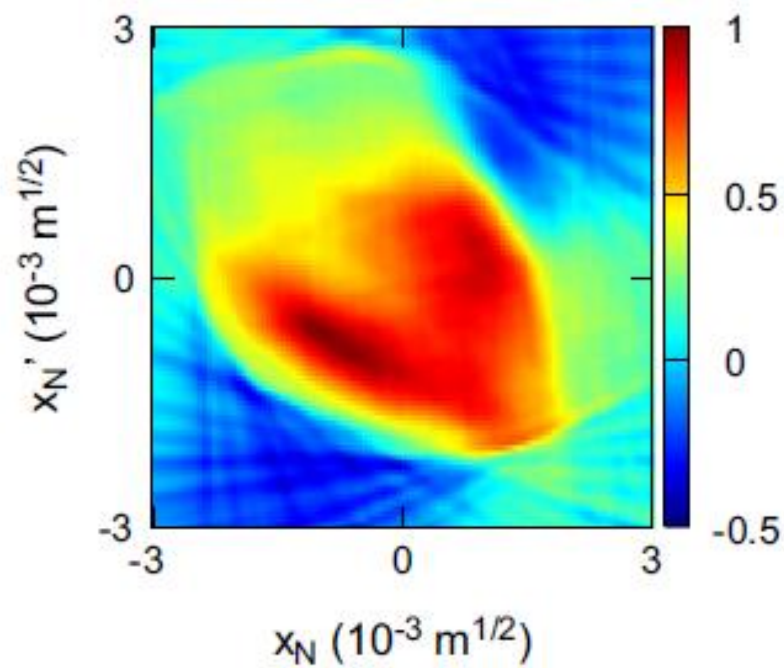


Reduction in the calculated emittance = 10%
(transverse rms size ~ 0.25 mm)

Space charge in the tomographic reconstruction (ALICE, Cockcroft Institute, UK)

- Application to quad-scan at ALICE [80 pC, 1.2 mm bunch length, 12 MeV]: reconstruction discrepancy from different measurements explained





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 more than 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 and 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.

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