HB2016, Malmö, Sweden

EMITTANCE RECONSTRUCTION TECHNIQUES IN PRESENCE OF SPACE CHARGE APPLIED DURING THE LINAC4 BEAM COMMISSIONING

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LINAC4 AND ITS COMMISSIONING STAGES

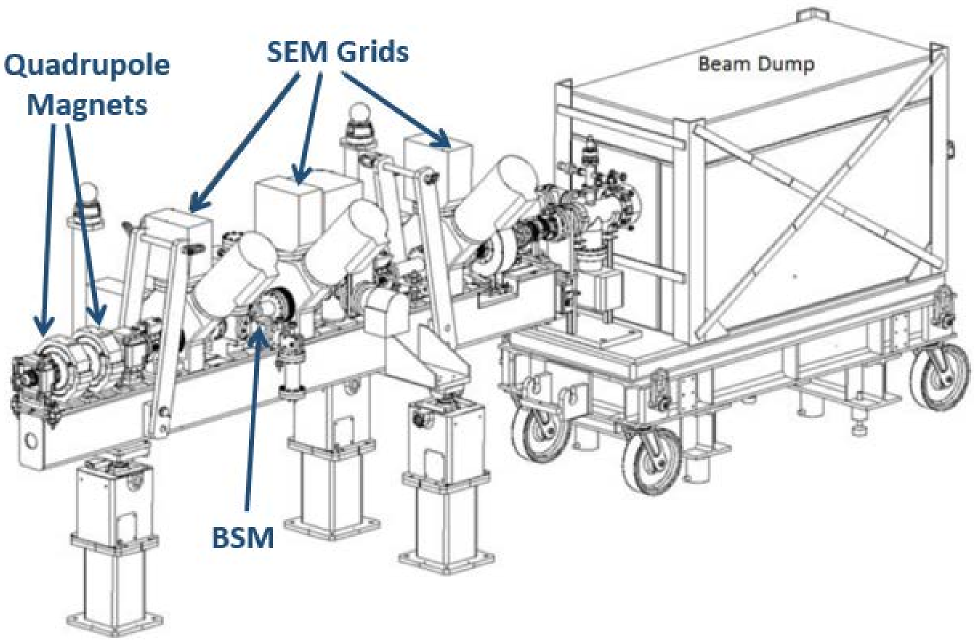
Talk on Monday: MOAM2P20 on Linac4 project.

The Linac4 commissioning is performed in several stages.

This talk will focus on the indirect emittance measurement methods in the presence of space charge and their applications during the 50 and 100 MeV beam commissioning.

High Energy Diagnostic Bench

Used during the beam commissioning at 50 and 100 MeV.

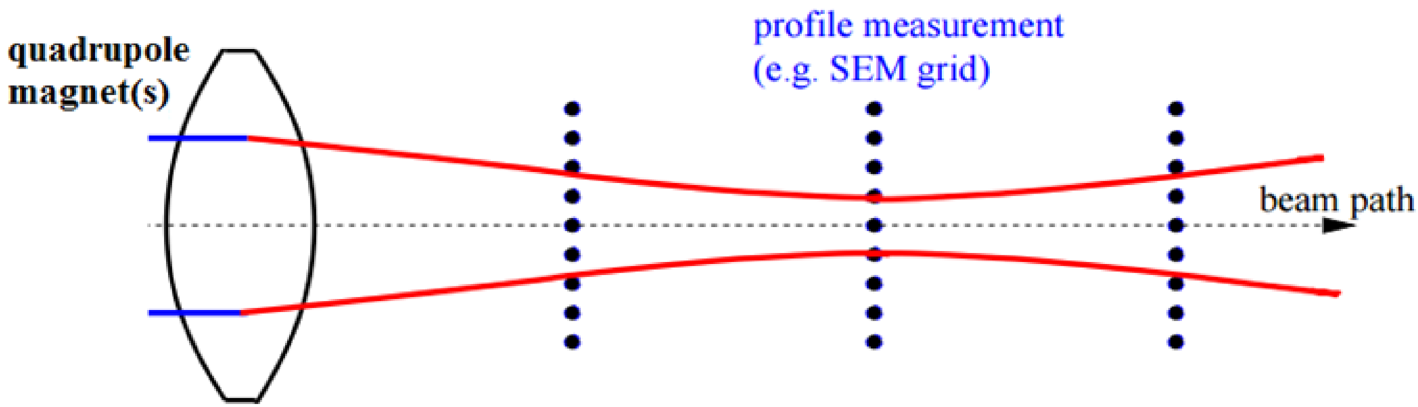


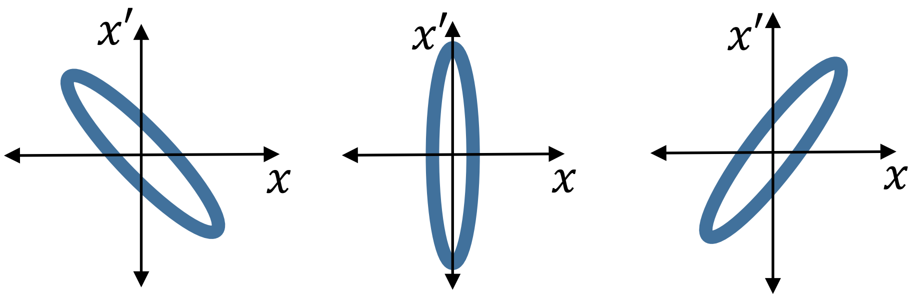
Indirect measurement of transverse emittance using measured beam profiles at three secondary electron emission (SEM) grids.

Indirect measurement of longitudinal emittance using measured beam profiles at bunch shape monitor (BSM).

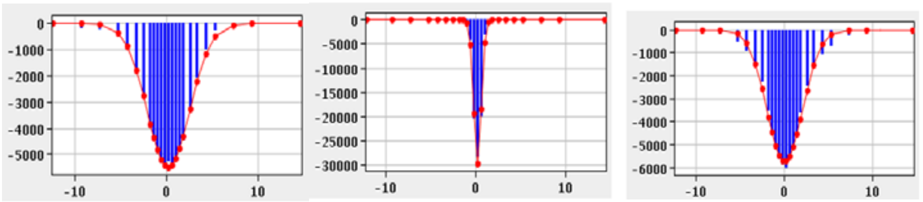
Space-charge must to be taken into account!

Indirect emittance measurement, 3 monitor method



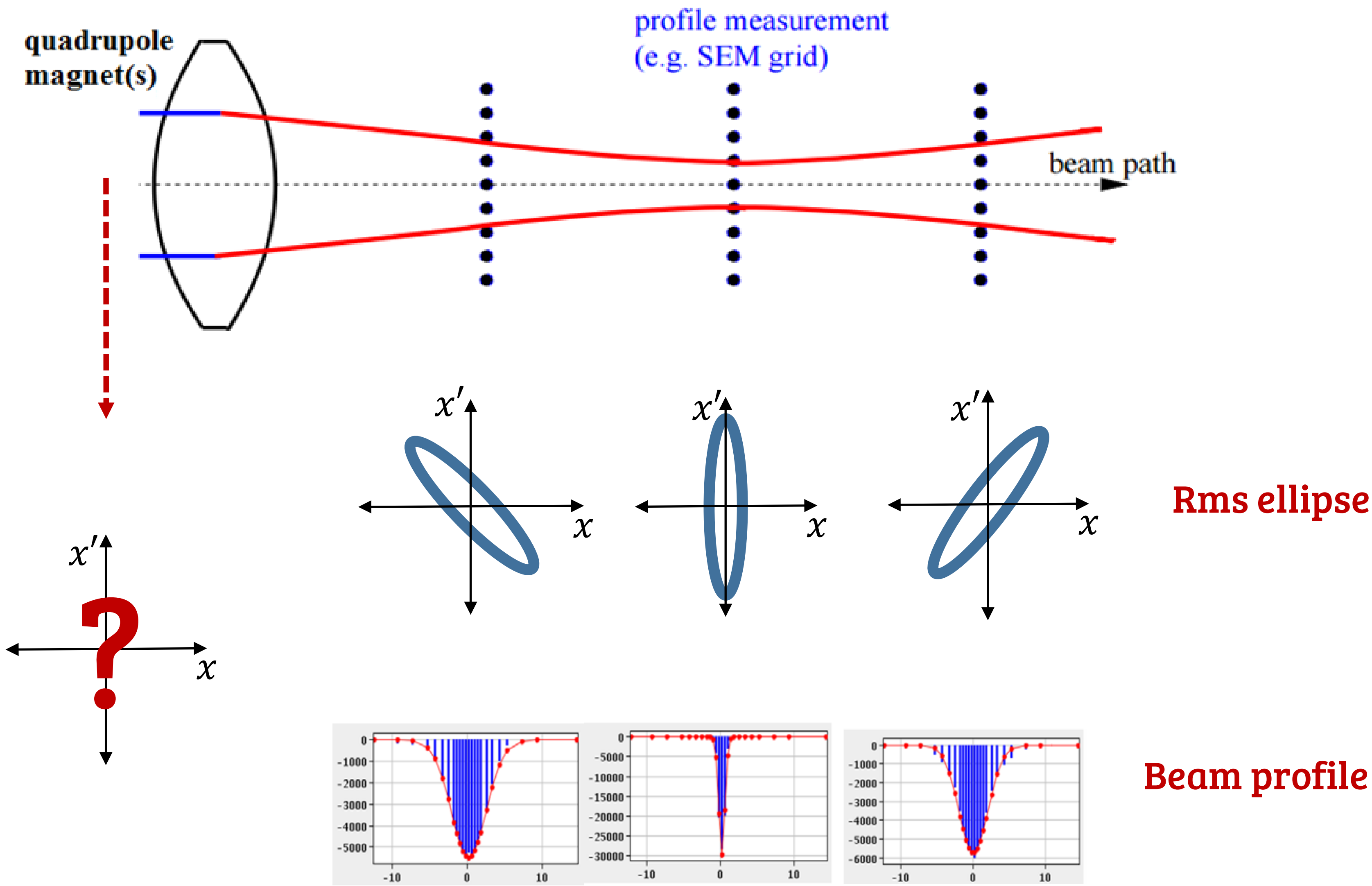


Rms ellipse

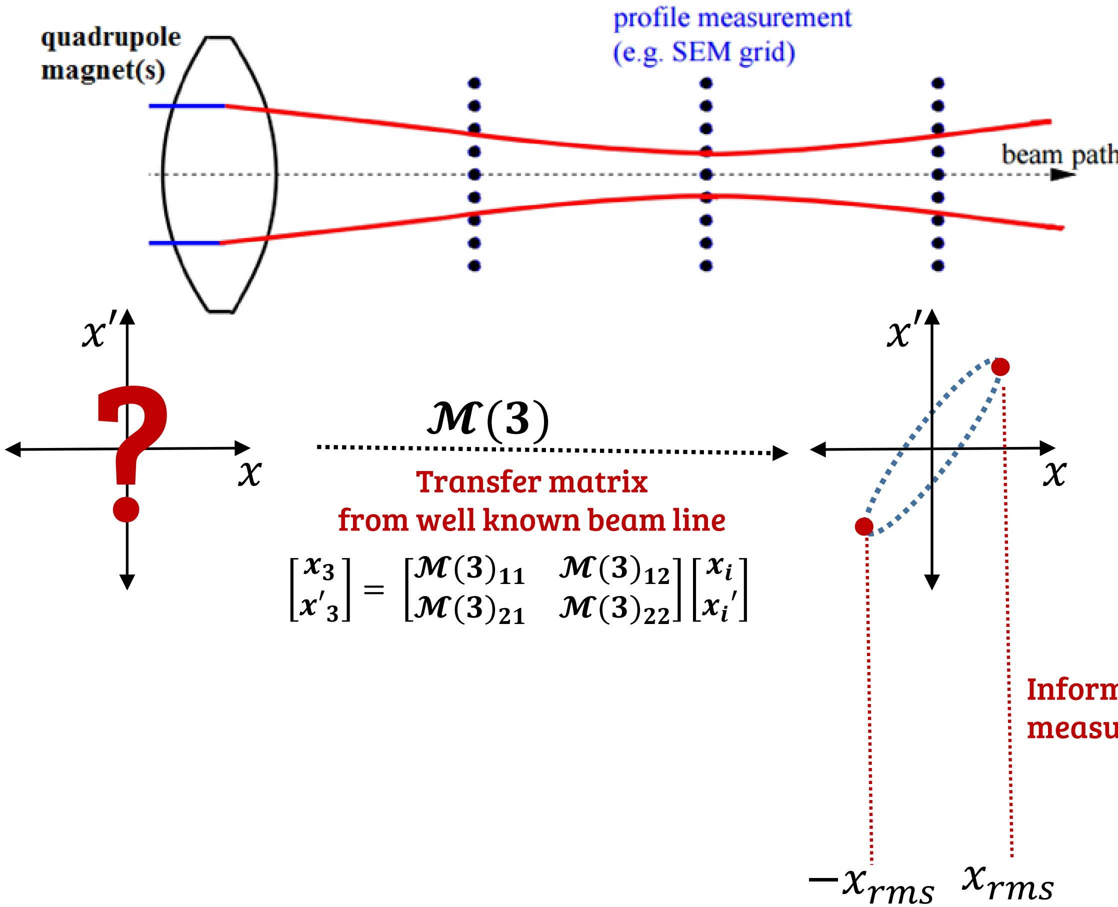


Beam profile

Indirect emittance measurement, 3 monitor method

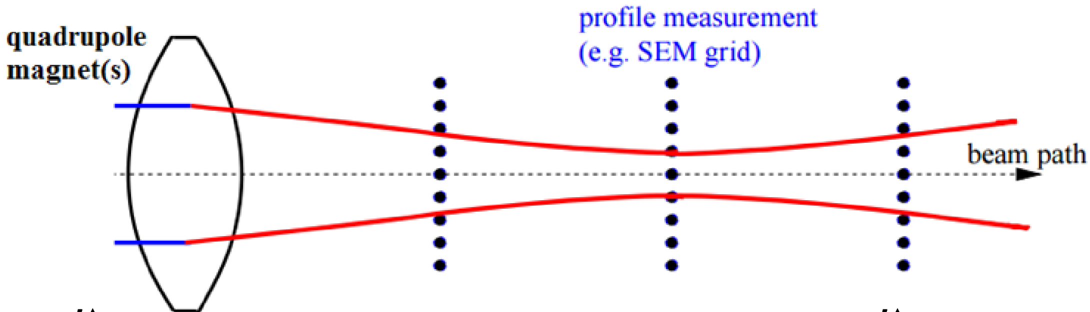


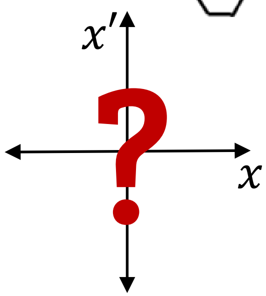
3 MONITOR METHOD, SPACE-CHARGE EFFECTS ARE IGNORED



$$\begin{bmatrix} x_3 \\ x'_3 \end{bmatrix} = \begin{bmatrix} \mathcal{M}(3)_{11} & \mathcal{M}(3)_{12} \\ \mathcal{M}(3)_{21} & \mathcal{M}(3)_{22} \end{bmatrix} \begin{bmatrix} x_i \\ x_i{}' \end{bmatrix}$$

3 MONITOR METHOD, SPACE-CHARGE EFFECTS ARE IGNORED

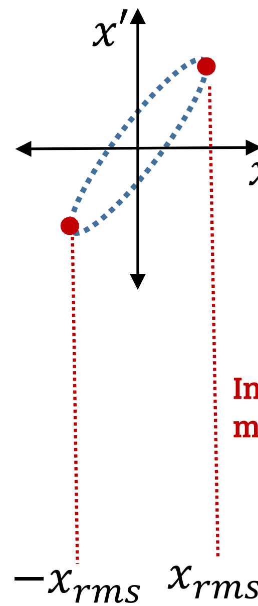




$\mathcal{M}(3)$

Transfer matrix
from well known beam line

$$\begin{bmatrix} x_3 \\ x'_3 \end{bmatrix} = \begin{bmatrix} \mathcal{M}(3)_{11} & \mathcal{M}(3)_{12} \\ \mathcal{M}(3)_{21} & \mathcal{M}(3)_{22} \end{bmatrix} \begin{bmatrix} x_i \\ x_i' \end{bmatrix}$$



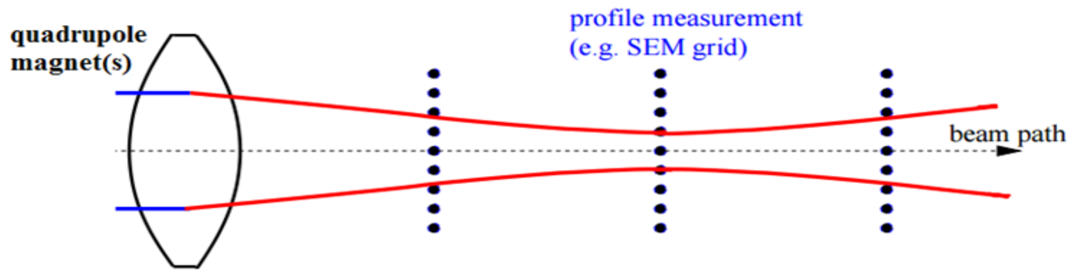
Information we get from the measured rms beam size!!!

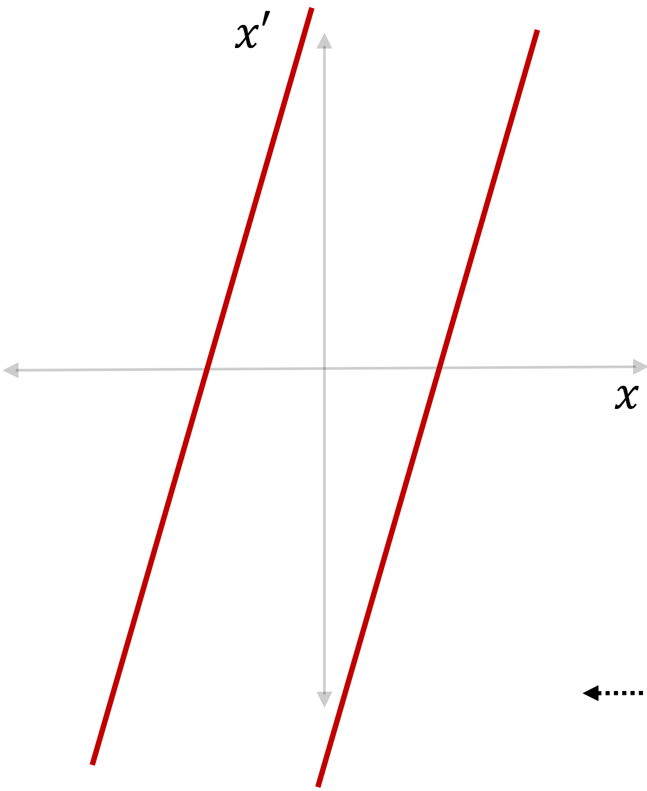
Where do they come from
in the initial phase space?

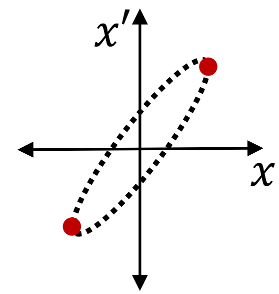
$$x_{rms} = \mathcal{M}(3)_{11} x_i + \mathcal{M}(3)_{12} x'_i$$

$$-x_{rms} = \mathcal{M}(3)_{11} x_i + \mathcal{M}(3)_{12} x'_i$$

3 MONITOR METHOD, SPACE-CHARGE EFFECTS ARE IGNORED



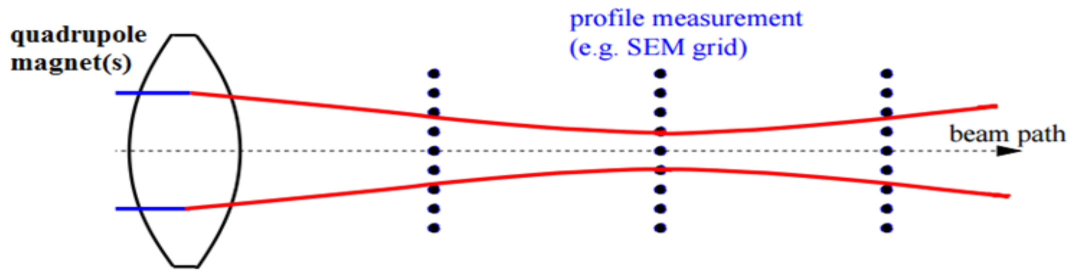


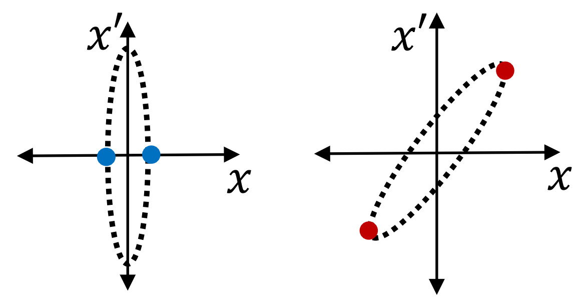


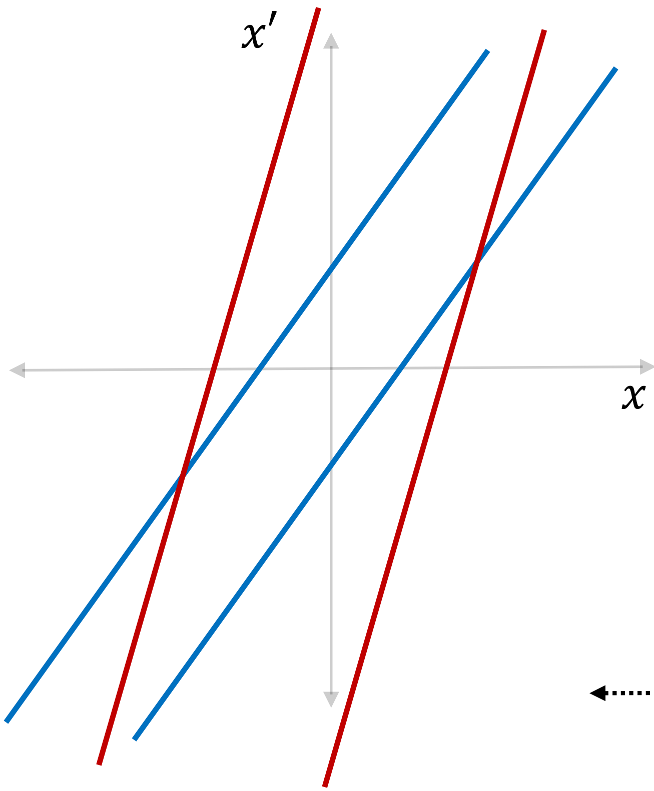
Linear mapping of the measured rms beam size onto the initial phase space.

Initial phase space

3 MONITOR METHOD, SPACE-CHARGE EFFECTS ARE IGNORED



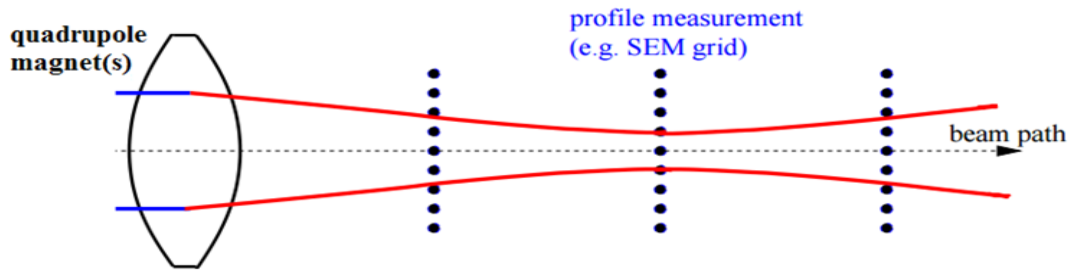


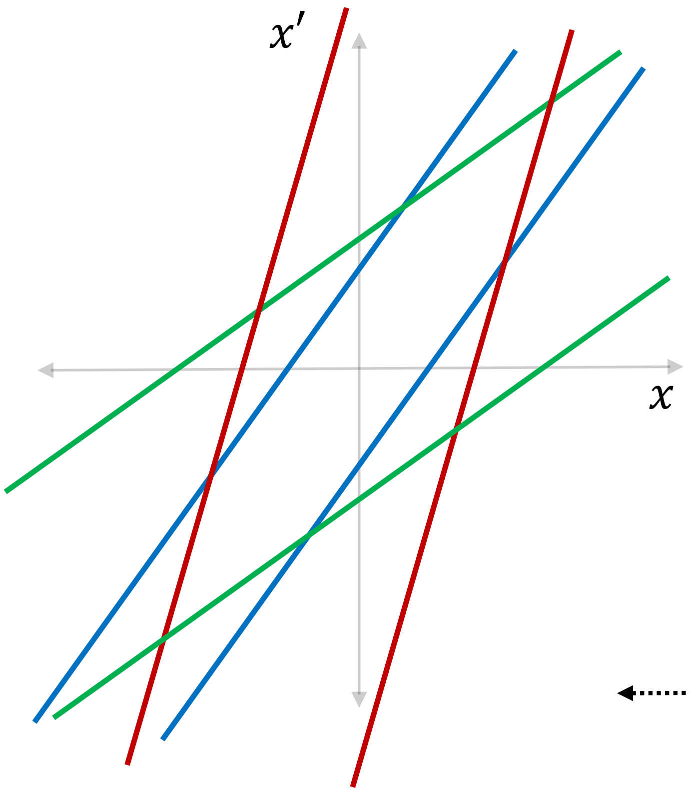


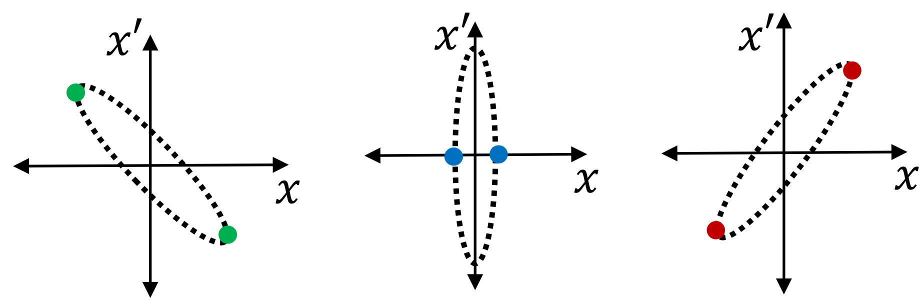
Linear mapping of the measured rms beam size onto the initial phase space.

Initial phase space

3 MONITOR METHOD, SPACE-CHARGE EFFECTS ARE IGNORED



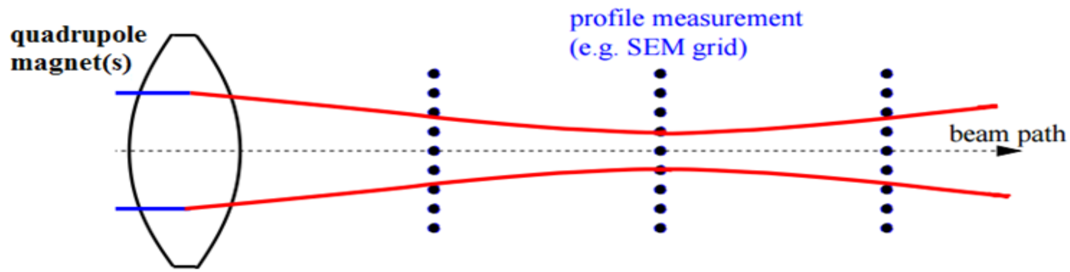


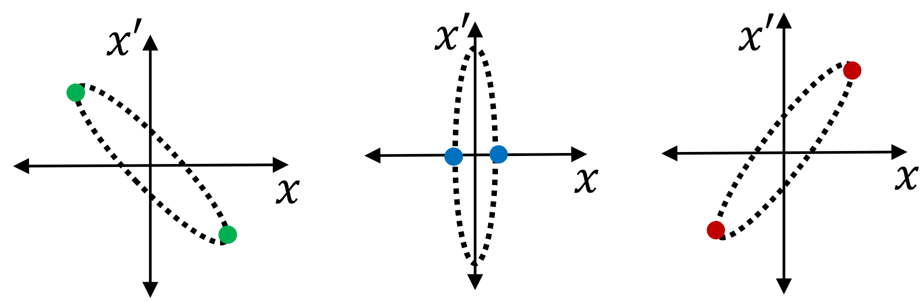


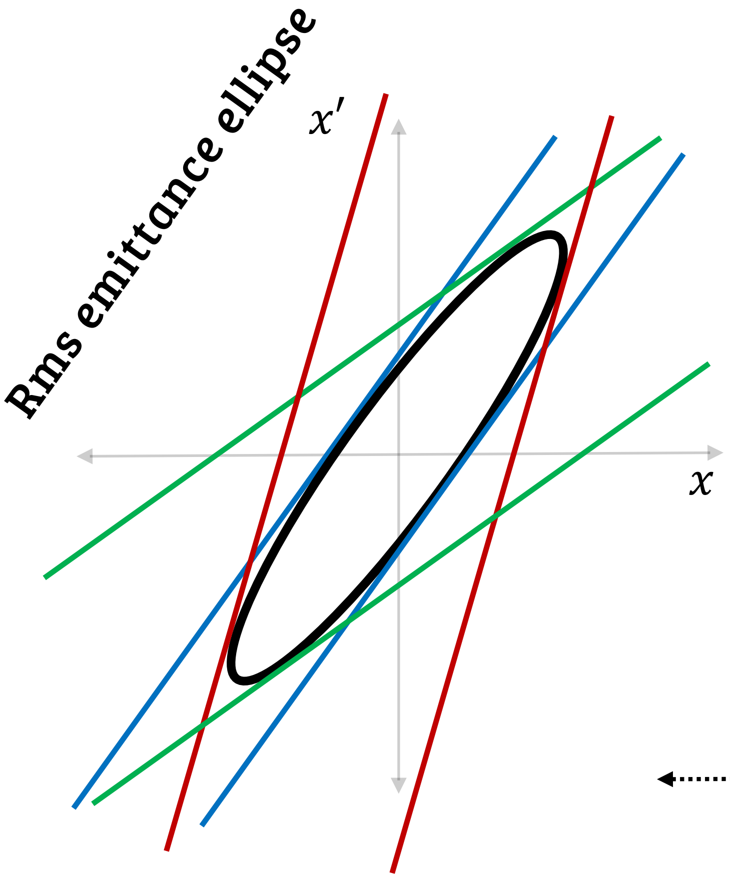
Linear mapping of the measured rms beam size onto the initial phase space.

Initial phase space

3 MONITOR METHOD, SPACE-CHARGE EFFECTS ARE IGNORED





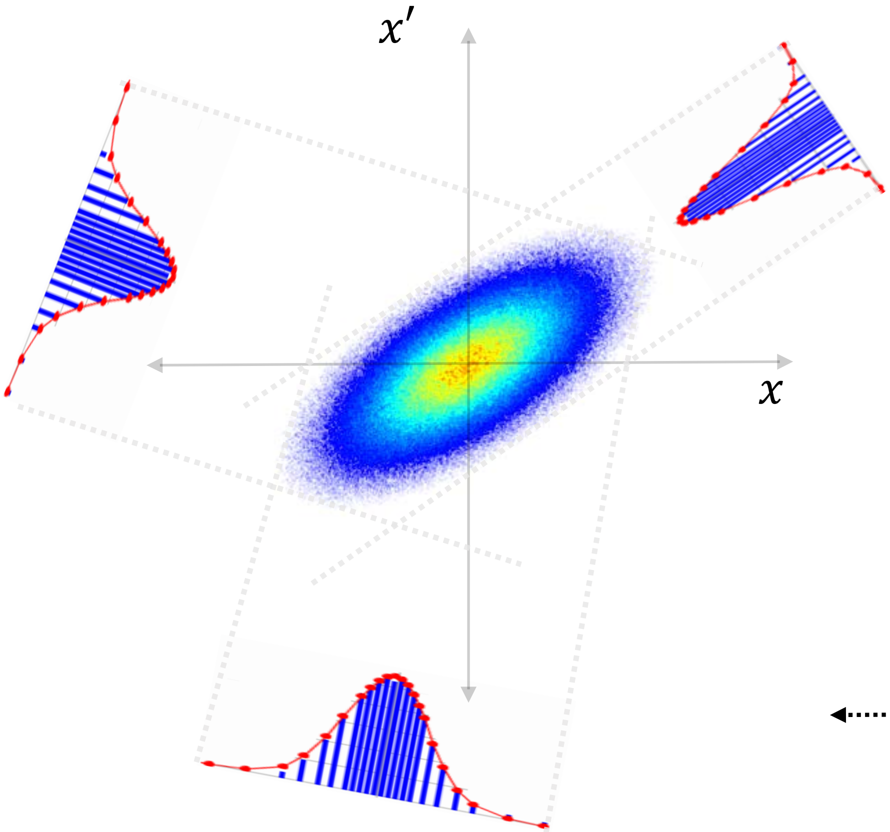


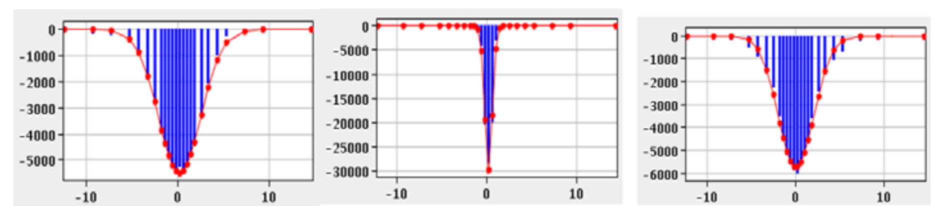
Linear mapping of the measured rms beam size onto the initial phase space.

Initial phase space

PHASE SPACE TOMOGRAPHY, SPACE-CHARGE EFFECTS ARE IGNORED

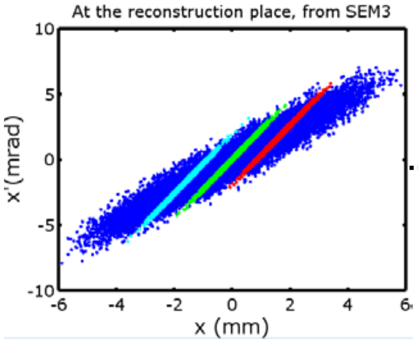
One can linearly map the measured profiles onto the initial phase space and use tomography to reconstruct the distribution of particle density in a phase space.





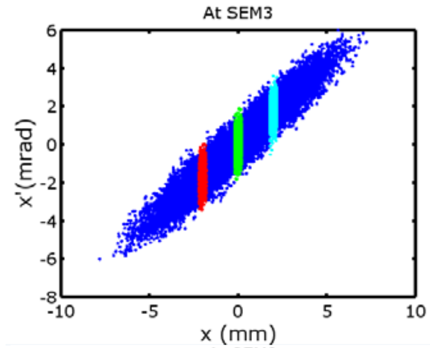
Linear mapping of the measured profiles onto the initial phase space.

What about space charge?

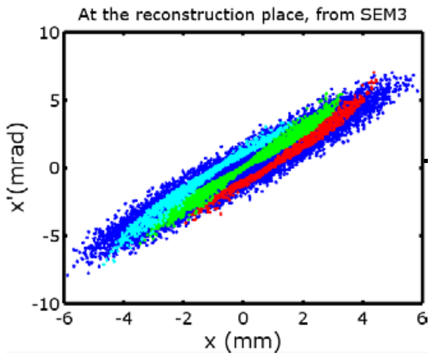


From the entrance of the bench

to SEM-3 no space-charge

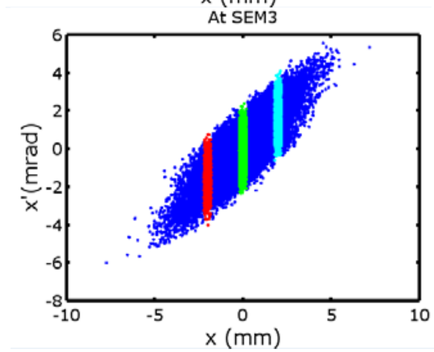


Transverse

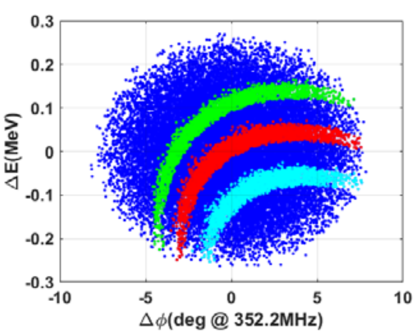


From the entrance of the bench

to SEM-3 with space-charge

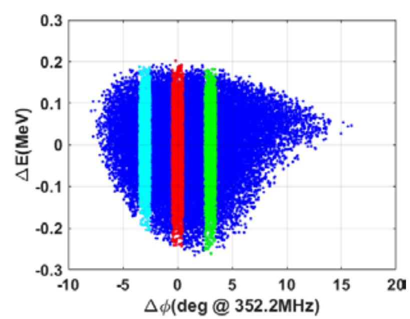


Transverse



Through the DTL tank3

no space-charge



Longitudinal

In the transverse planes, in case of space-charge, linear mapping is not possible!

In the longitudinal plane the situation is even more complex.

Including the Effects of Space Charge

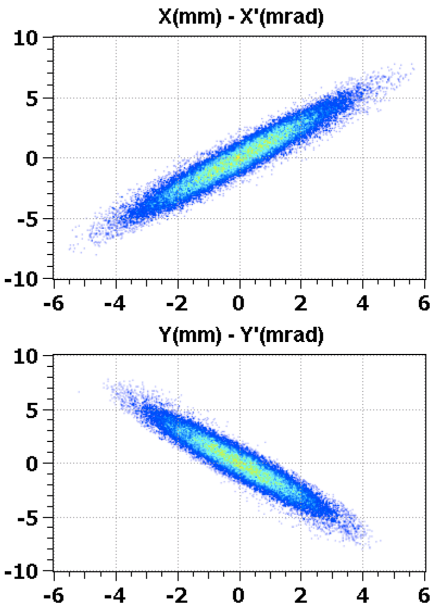
We can extend the classical methods by combining them with multi-particle tracking including space-charge effects.

For the indirect emittance measurements in the presence of space charge, two methods were developed, tested and applied during the Linac4 commissioning

- **The “Forward Method”**
  - Takes measured rms beam sizes as input.
  - Estimates rms emittance, alpha and beta.
  - Simpler but still very powerful.
- **Hybrid phase space tomography**
  - Takes measured beam profiles as input.
  - More sophisticated, estimates phase space density.

Both methods use multi-particle tracking including space-charge!

The Forward Method



- Modify emittance, alpha, beta
- Simulate (with space-charge) to the measurement locations with the optics used while taking the measurements.
- Compare the simulated rms beam sizes with the measured ones.
- Repeat the process iteratively until simulated rms beam sizes converge to the measured ones.

3 horizontal beam size from 3 monitors

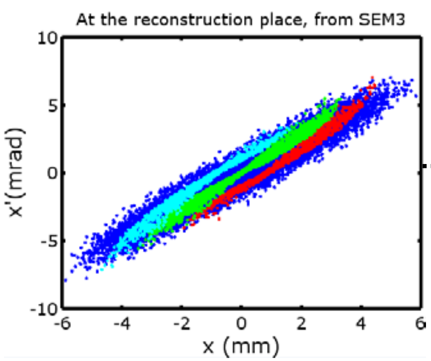
3 vertical beam size from 3 monitors

➢ For accurate space charge calculations, initial description of the particle distribution in all phase spaces is important.

J-B. Lallement, A.M. Lombardi and P.A. Posocco, "Linac4 beam commissioning strategy", *in Proc. HB'12*, Beijing, China, Sept. 2012, 283-285.

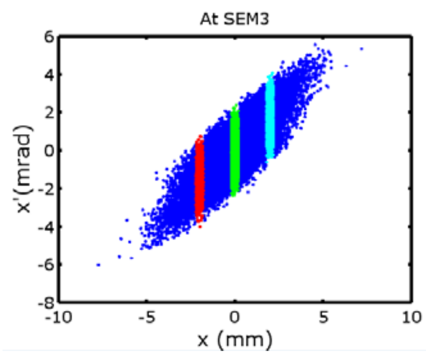
Hybrid Phase Space Tomography

- Hybrid phase-space tomography combines multi-particle tracking (including space-charge) and tomography.
- Travel is used for the multi-particle tracking.
- Travel can give initial coordinates of any selected particles along the beam line. Simplifies mapping even in the case of nonlinear mapping.



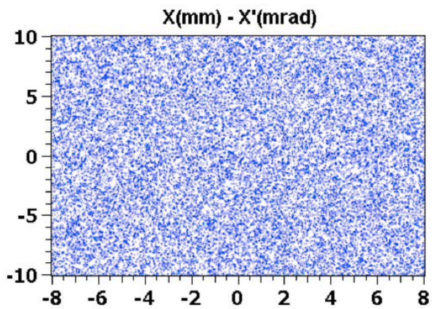
From the entrance of the bench

to SEM-3 with space-charge



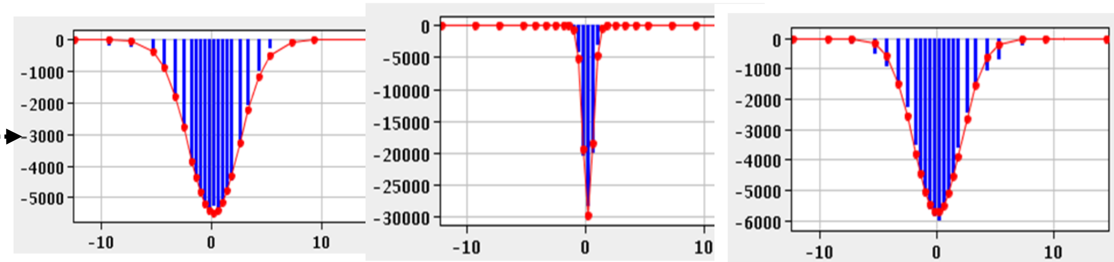
Transverse

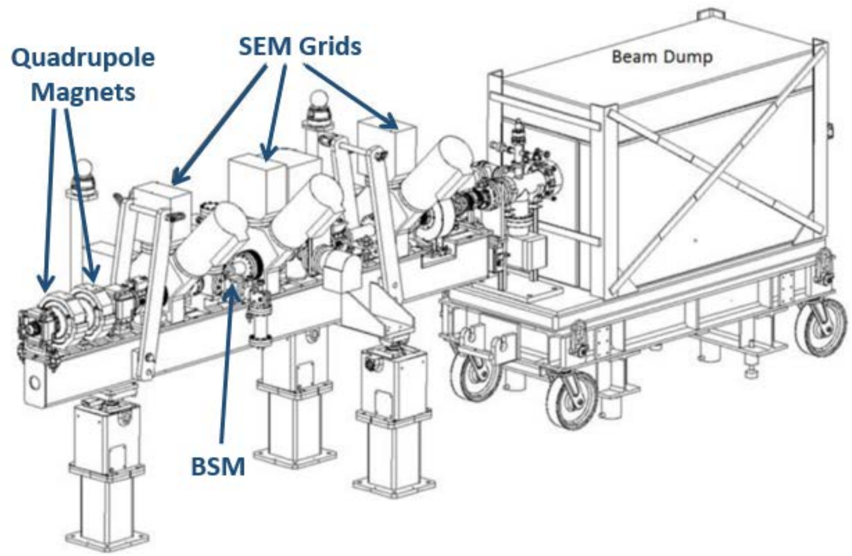
HYBRID PHASE SPACE TOMOGRAPHY



Simulate
with space-charge

Binned measurement data from 3 monitors

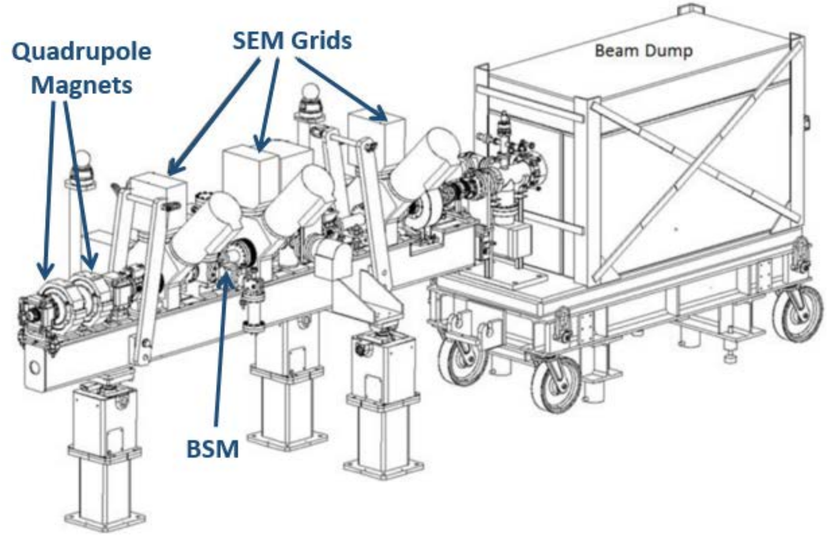


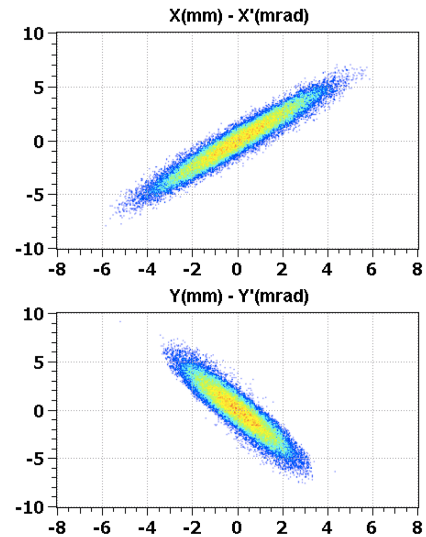


- **Simulate the initial test beam by including space-charge.**
- **Find which particles fall on which wires.**
- **Deduce the new distribution of density in the phase space.**
- **Generate a new beam distribution and use it for the next iteration.**

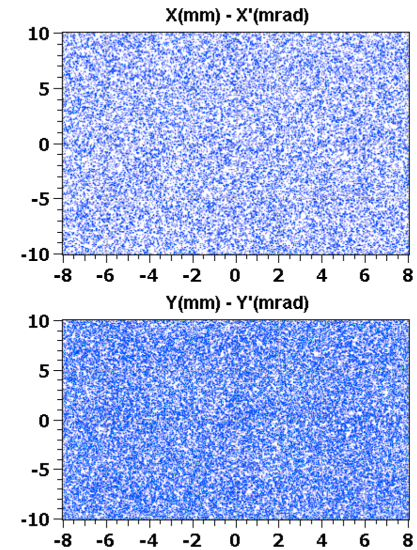
Testing the method

- A reference beam (50MeV H- beam with 20mA beam current) is tracked to the profile monitors with two different optics settings to simulate measurements (one for horizontal one for vertical measurements).
- The beam profiles are saved and given as input to the hybrid phase space tomography routine.
- A beam with uniform distribution and big horizontal and vertical emittance was used as a test beam.
- Longitudinal distribution of the test beam is identical to that of the reference beam.





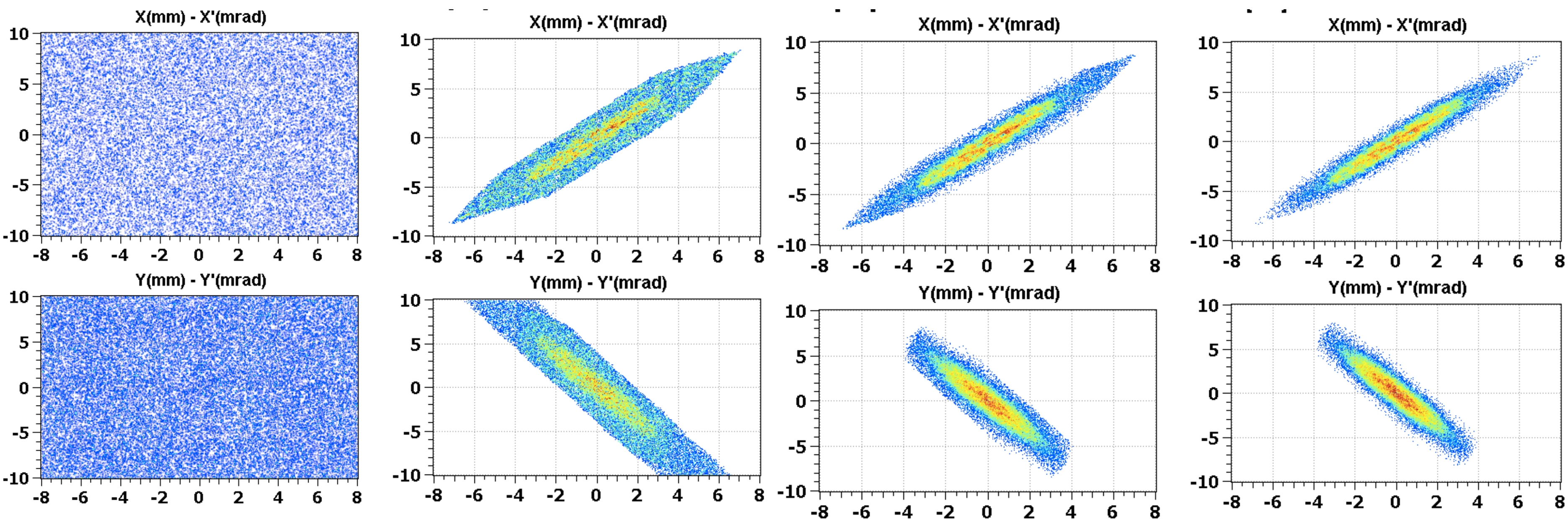
Transverse phase space plots of the reference beam



Transverse phase space plots of the test beam

EVOLUTION OF THE HORIZONTAL AND VERTICAL PHASE SPACES

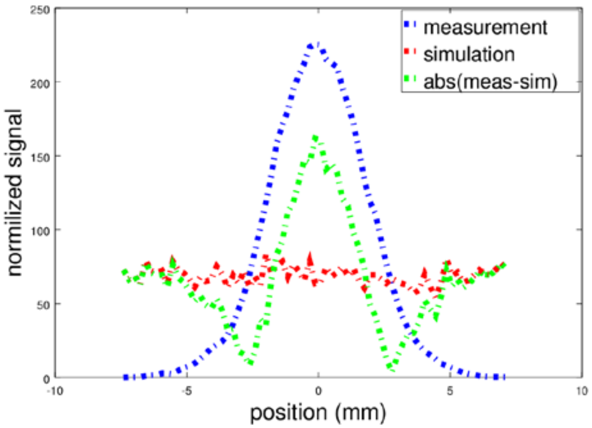
Initial test beam | 2^{nd} iteration | 5^{th} iteration | 10^{th} iteration



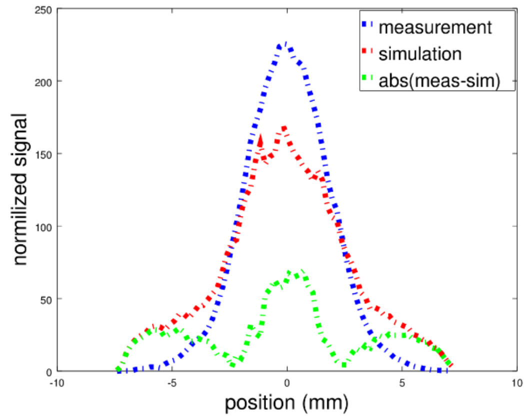
AN EXAMPLE OF MEASURED AND SIMULATED PROFILE

Horizontal profile at the 3rd SEM grid

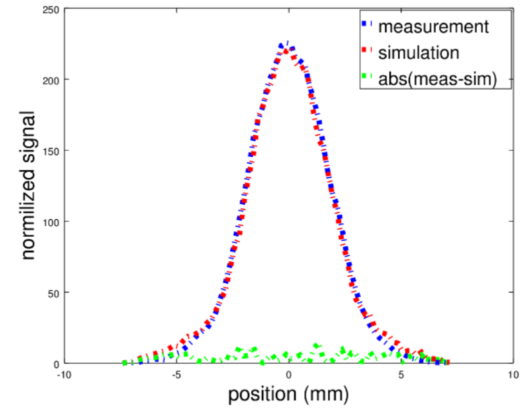
After the 1st iteration



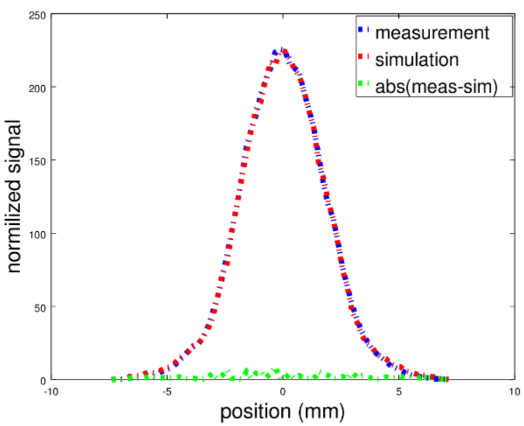
After the 3rd iteration

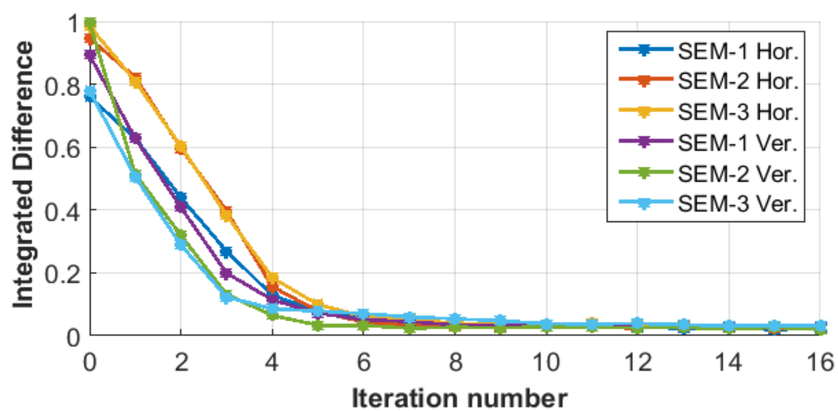


After the 6th iteration



After the 16th iteration

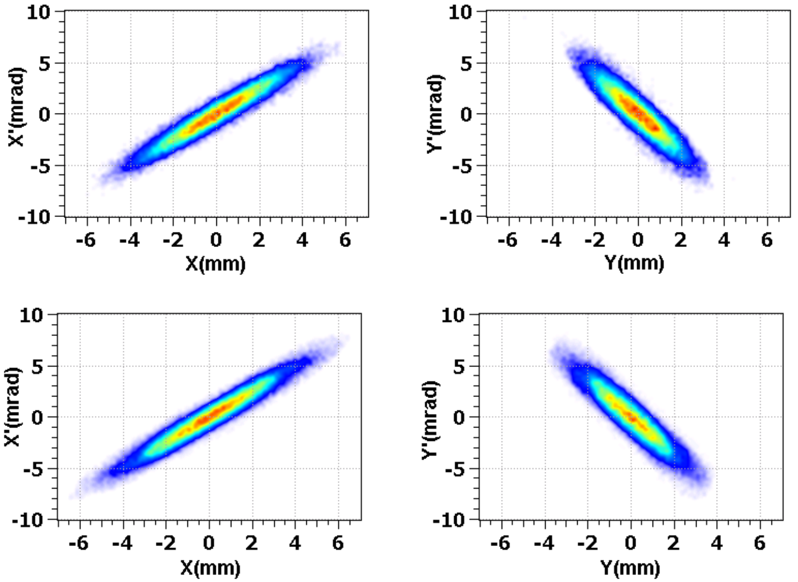




Discrepancy:integral of absolute difference

TESTING THE HYBRID PHASE SPACE TOMOGRAPHY

With 50 Mev 20 mA H- beam



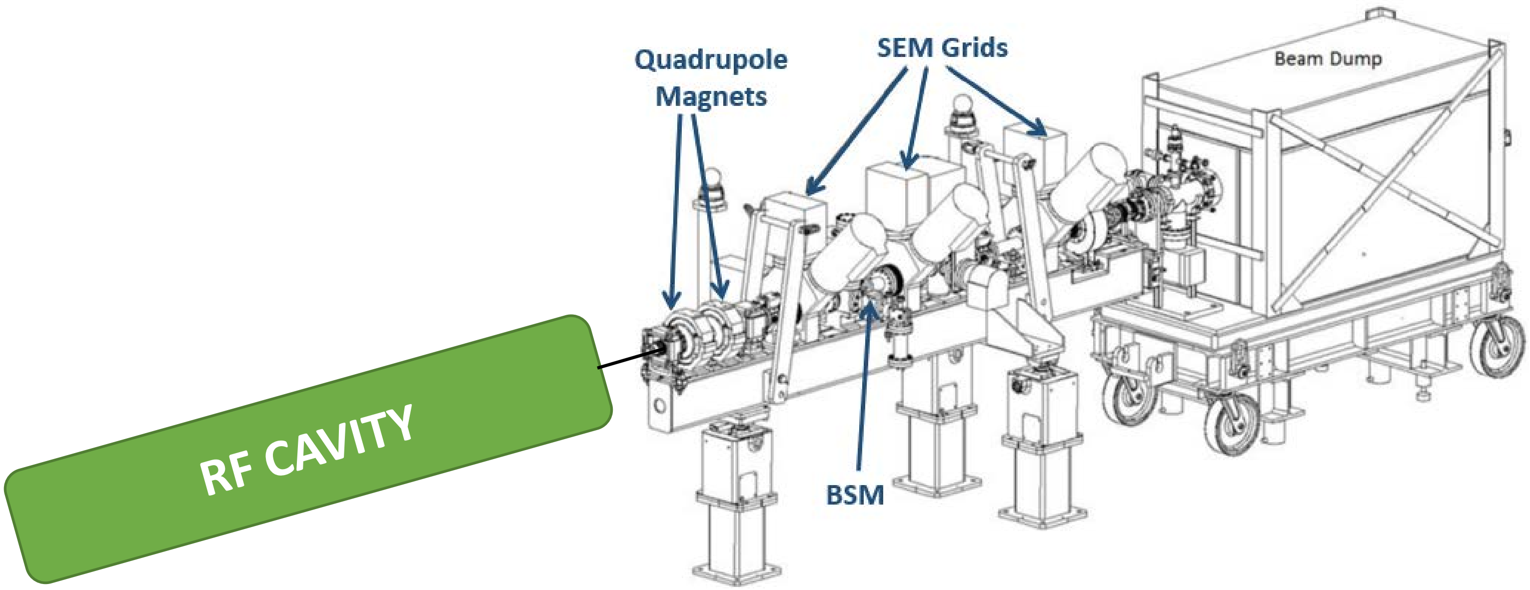
Transverse phase space plots of the reference beam (top row) and the reconstructed beam (bottom row).

Parameter	Reference	Reconstructed
ε_x (rms)	0.39 π.mm.mrad	0.40 π.mm.mrad
α_x	-3.47	-3.81
β_x	2.86 mm/π.mrad	3.14 mm/π.mrad
ε_y (rms)	0.35 π.mm.mrad	0.36 π.mm.mrad
α_y	2.35	2.49
β_y	1.28 mm/π.mrad	1.39 mm/π.mrad

Twiss parameters (emittance is normalized) of the reference and reconstructed beams

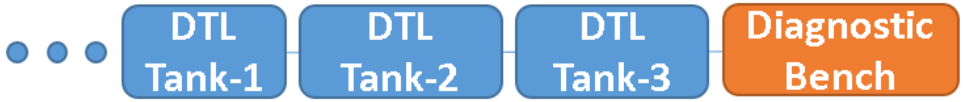
Each phase space is reconstructed using 3 profiles. More profiles will improve the reconstruction.

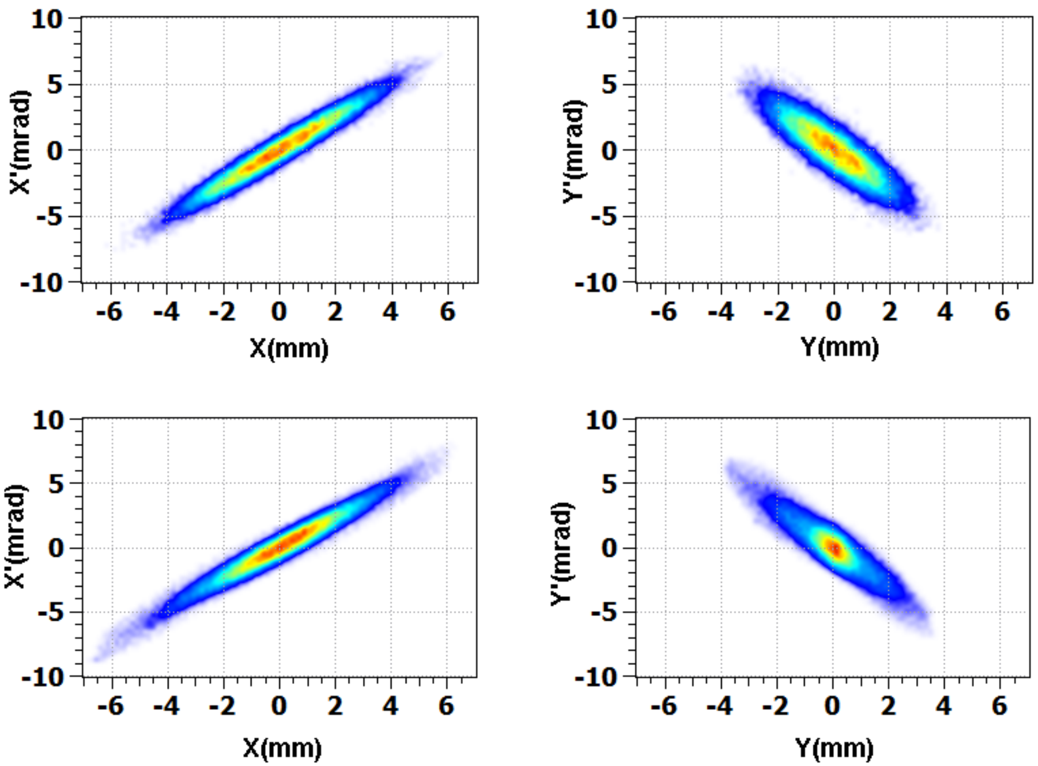
Application to the Longitudinal Plane



Both forward method and hybrid phase space tomography can be applied to the longitudinal phase space reconstruction where the phase and/or amplitude of an RF cavity is varied and the phase or momentum profile is measured downstream. In the case of Linac4, phase spread was measured by a BSM.

50 MeV Commissioning - Transverse





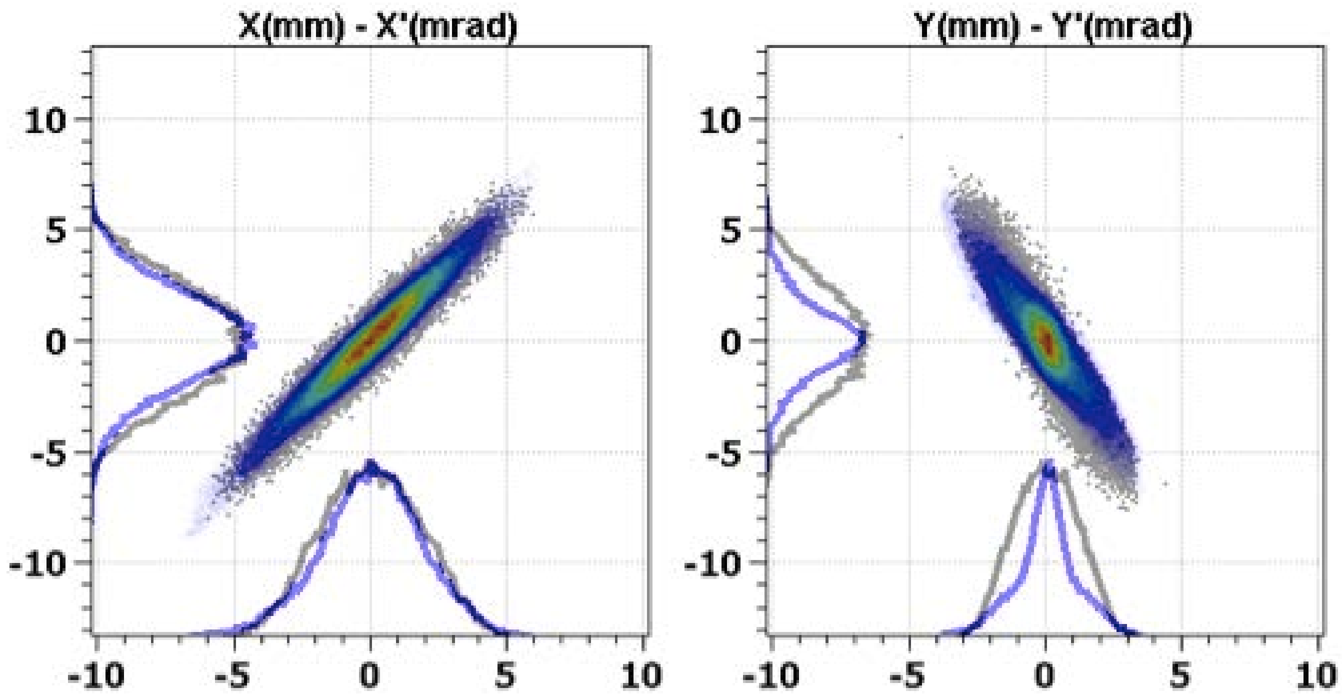
Forward method

ε_x (rms)= 0.32 π.mm.mrad
ε_y (rms)= 0.36 π.mm.mrad

Hybrid phase space tomography

ε_x (rms)= 0.33 π.mm.mrad
ε_y (rms)= 0.32 π.mm.mrad

Comparison of expected and measured beams



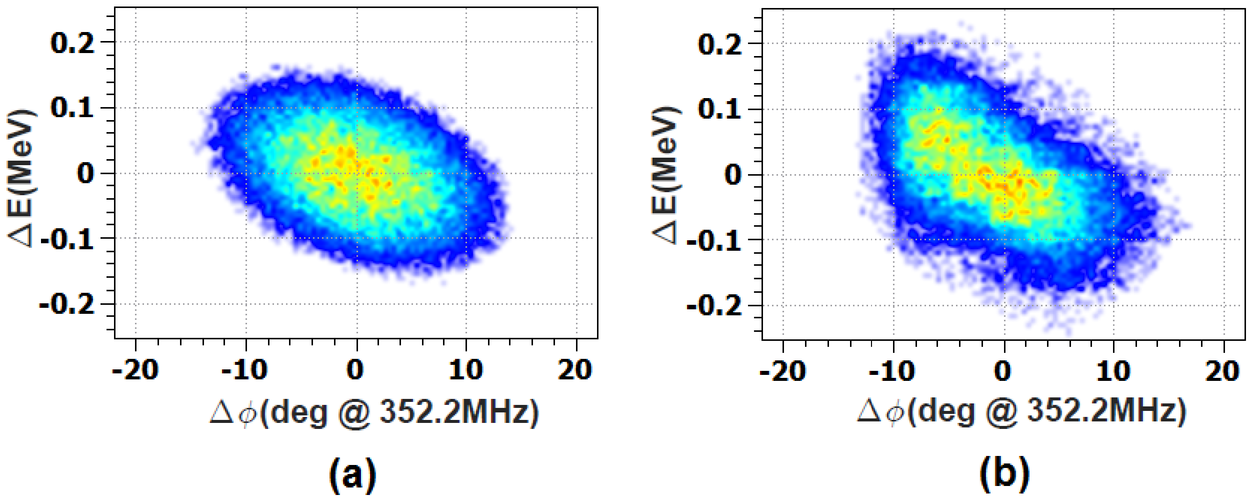
Comparison of phase space plots of the expected beam (grayscale) and measured at 50 MeV (colour scale) after the DTL.

50 MeV Commissioning - Longitudinal

DTL tank 3 RF phase was varied and the phase profile of the beam was measured at the BSM on the diagnostic bench.

Measured –forward method

Measured – phase space tomography

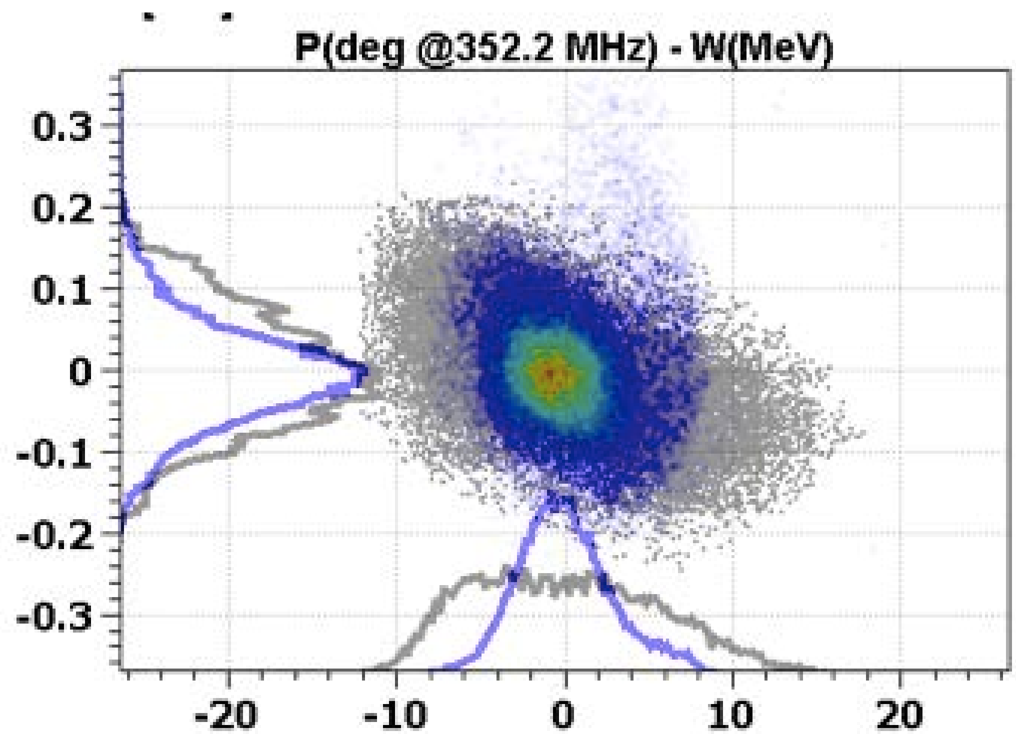


30 MeV
Before DTL Tank3

ε (rms)= 0.29 π.deg.MeV

ε (rms)= 0.33 π.deg.MeV

50 MeV Commissioning - Longitudinal

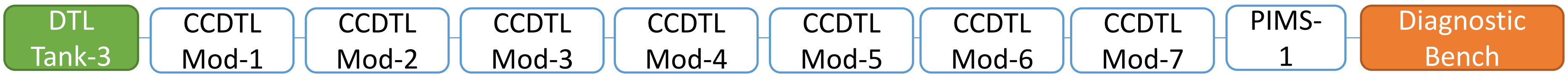


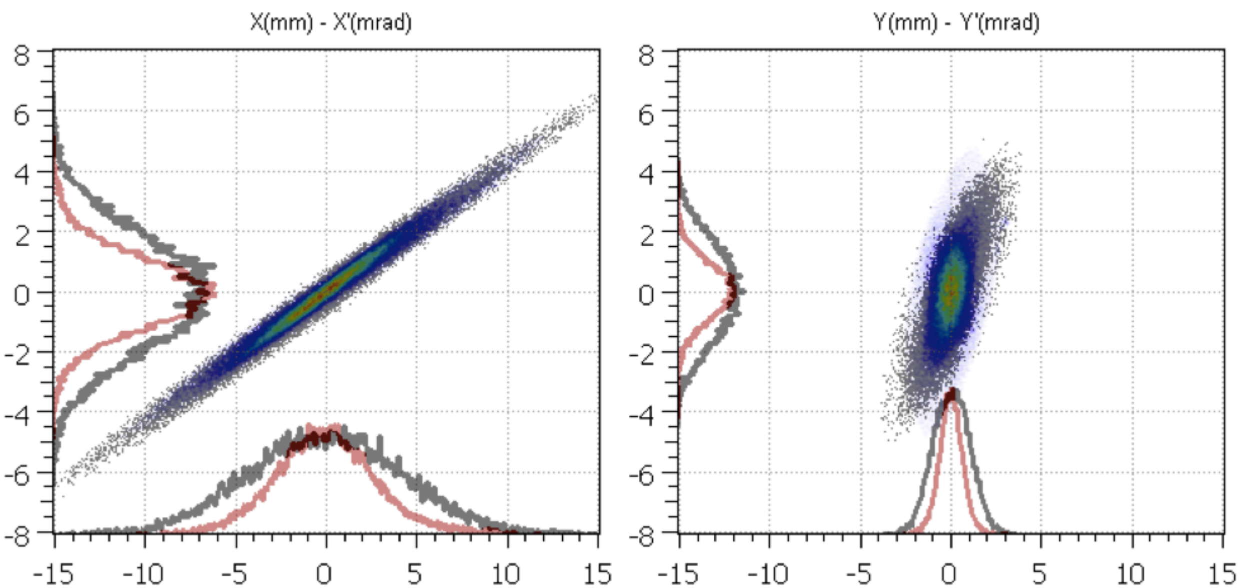
30 MeV
Before DTL Tank3

Comparison of the phase space plots of the measured (grayscale) and expected (colour scale) beams at the entrance of the DTL tank 3 at 30 MeV.

100 MEV COMMISSIONING

Beam at 50 MeV



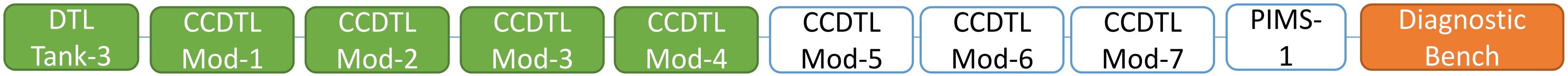


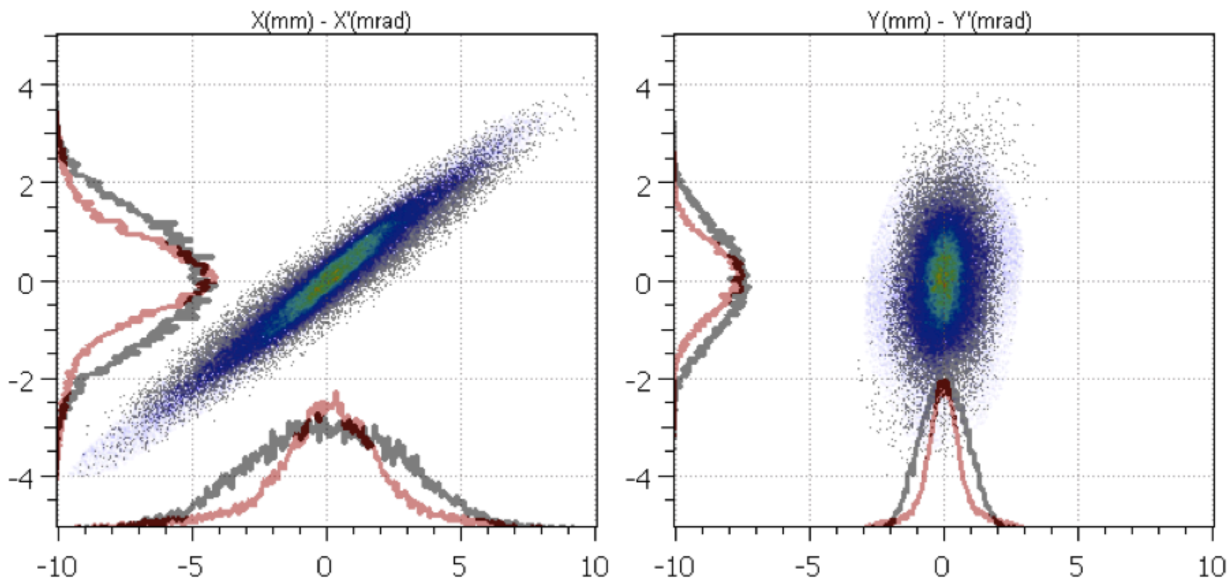
Comparison of the phase space plots of the expected (grayscale) and measured (colour scale) beams at 50 MeV.

Measurements with hybrid phase space tomography.

100 MEV COMMISSIONING

Beam at 80 MeV

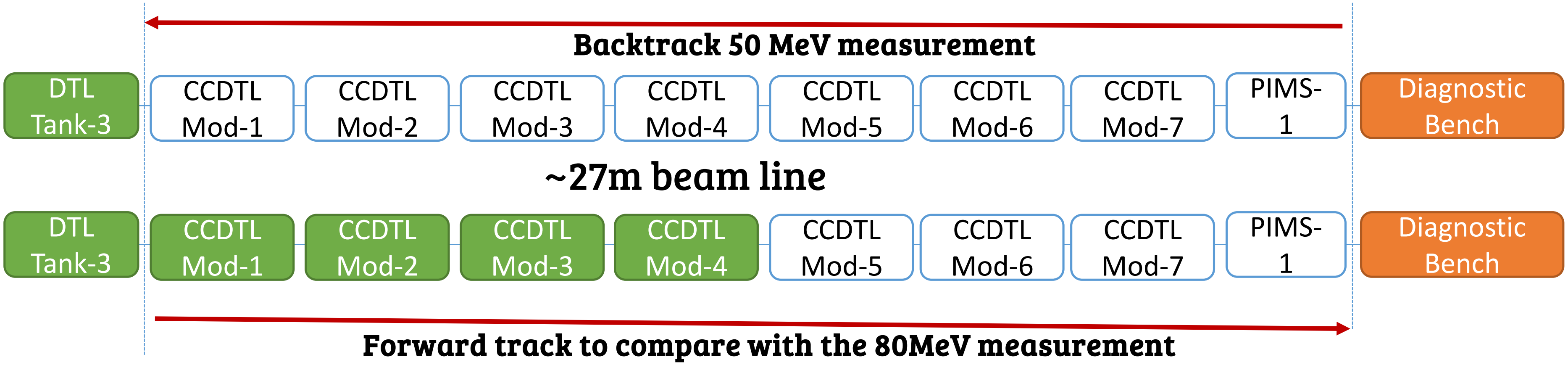


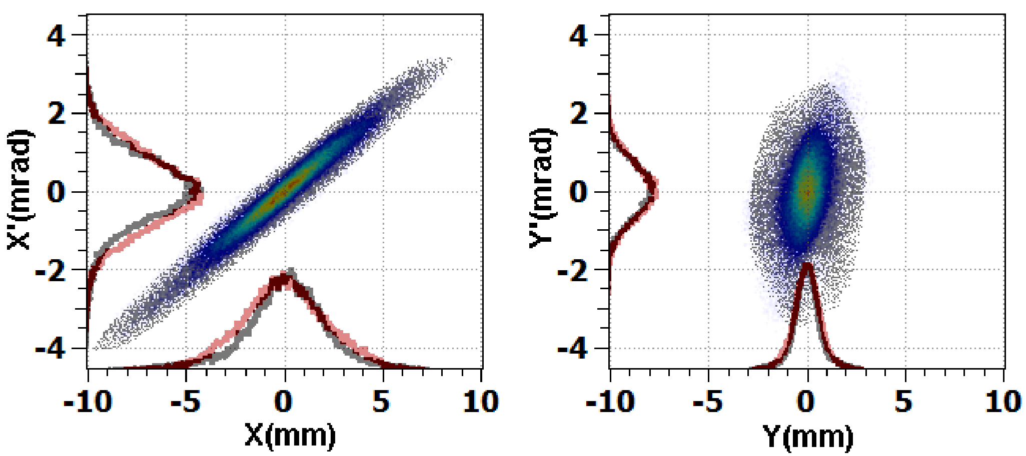


Comparison of the phase space plots of the expected (grayscale) and measured (colour scale) beams at 80 MeV.

Measurements with hybrid phase space tomography.

COMPARISON OF THE TWO MEASUREMENTS





Comparison of the phase space plots of the beams measured at 80MeV (grayscale) and measured at 50 MeV then tracked to 80MeV (colour scale).

Parameter	50 MeV tracked to 80 MeV	Measured at 80 MeV
ε_x (rms)	0.22 π.mm.mrad	0.23 π.mm.mrad
α_x	-4.5	-4.6
β_x	10.7 mm/π.mrad	10.6 mm/π.mrad
ε_y (rms)	0.26 π.mm.mrad	0.27 π.mm.mrad
α_y	-0.49	-0.19
β_y	1.03 mm/π.mrad	1.02 mm/π.mrad

Twiss parameters (emittance is normalized) of the beams measured at 80MeV and measured at 50 MeV then tracked to 80MeV.

CONCLUSION

- The “forward method” and the “hybrid phase space tomography” were developed, validated and successfully applied during the Linac4 commissioning.
- The methods allow indirect measurement of the transverse and longitudinal emittance based on profile measurements in the presence of space charge.
- Both methods give consistent results with each other for the prediction of the rms ellipse parameters.
- Moreover, the hybrid phase space tomography allows reconstruction of the phase space density.
- Both methods will be used during the beam commissioning at 160 MeV and permanently during the operation of Linac4 at the end of the linac, as well as at the PS Booster injection.

SOME COMMENTS

- Comparison of measured and expected beam distributions along the linac helped us validate the settings and the correct operation of the linac.
- Measurement of emittance at each commissioning stage made our job easier during the next one and saved us time!
- Provided that the permanent profile monitors are enough and at the correct locations, these methods can also be used during operation without changing the optics.

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THANK YOU!