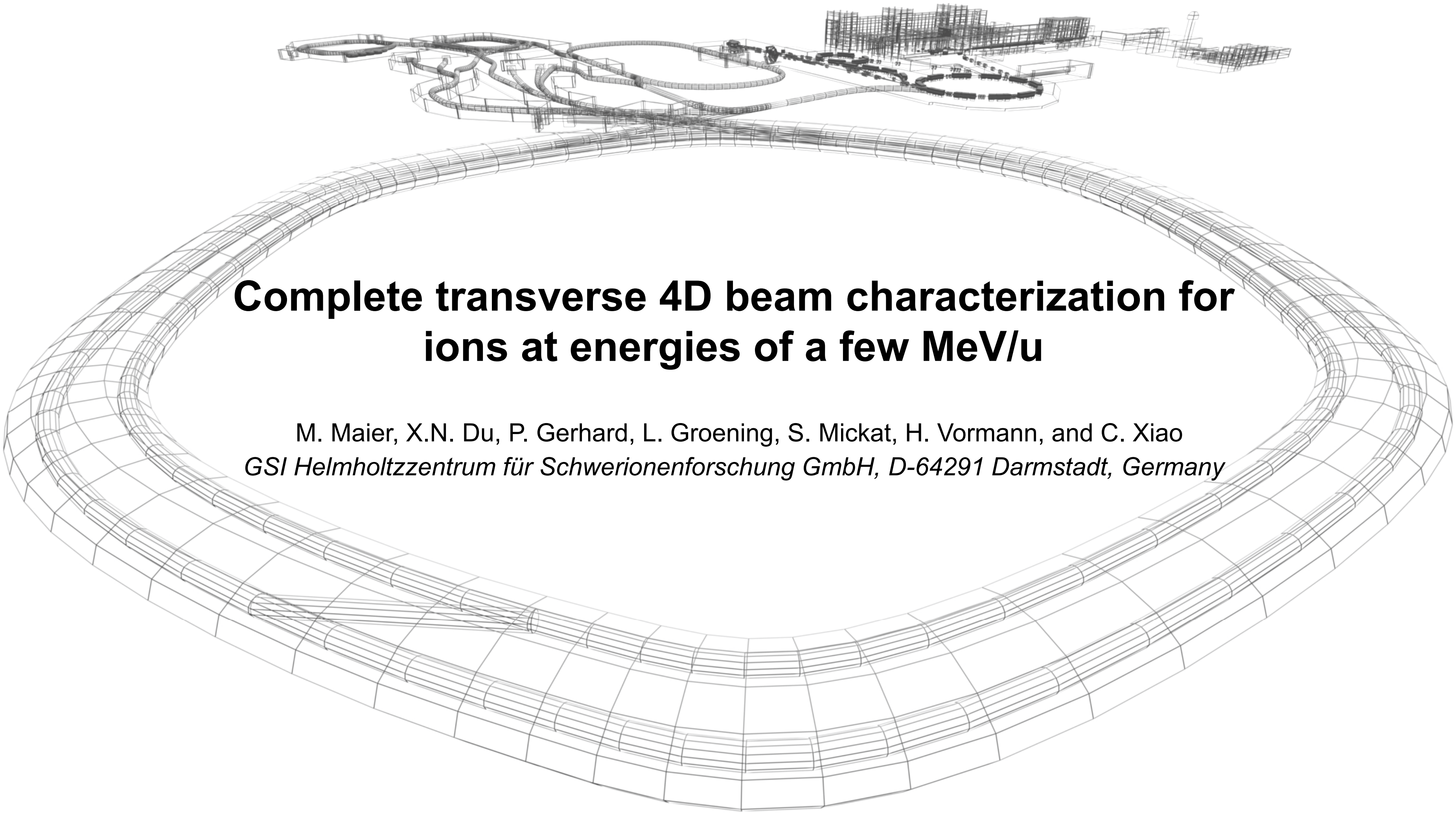

Complete transverse 4D beam characterization for ions at energies of a few MeV/u

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  - slit-grid Emittance scanners
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Introduction
equations for transverse emittance

The four-dimensional symmetric beam matrix C:
For a decoupled beam the off-diagonal matrix elements (red) are zero.

$$C = \begin{bmatrix} \langle xx \rangle & \langle xx' \rangle & \langle xy \rangle & \langle xy' \rangle \\ \langle x'x \rangle & \langle x'x' \rangle & \langle x'y \rangle & \langle x'y' \rangle \\ \langle yx \rangle & \langle yx' \rangle & \langle yy \rangle & \langle yy' \rangle \\ \langle y'x \rangle & \langle y'x' \rangle & \langle y'y \rangle & \langle y'y' \rangle \end{bmatrix}$$

with $\varepsilon_x = \sqrt{(det\ \sigma_x)}$

$$\boldsymbol{\sigma} = \begin{pmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{12} & \sigma_{22} \end{pmatrix} = \varepsilon \cdot \begin{pmatrix} \beta & -\alpha \\ -\alpha & \gamma \end{pmatrix}$$

$$\varepsilon_x = \sqrt{\det \boldsymbol{\sigma}} = \sqrt{\sigma_{11}\sigma_{22} - \sigma_{12}^2}$$

α, β, γ are the Twiss parameters and ε_x is the horizontal rms-emittance

Introduction
if the beam is not decoupled?

The four-dimensional rms emittance: $\varepsilon_{4d} = \varepsilon_1 \varepsilon_2 = \sqrt{detC}$

Diagonalization of the beam matrix yields the Eigen-emittances ε_1 and ε_2 which are:

$$\varepsilon_1 = \frac{1}{2}\sqrt{-tr[(CJ)^2] + \sqrt{tr^2[(CJ)^2] - 16det(C)}}$$

$$\varepsilon_2 = \frac{1}{2}\sqrt{-tr[(CJ)^2] - \sqrt{tr^2[(CJ)^2] - 16det(C)}}$$

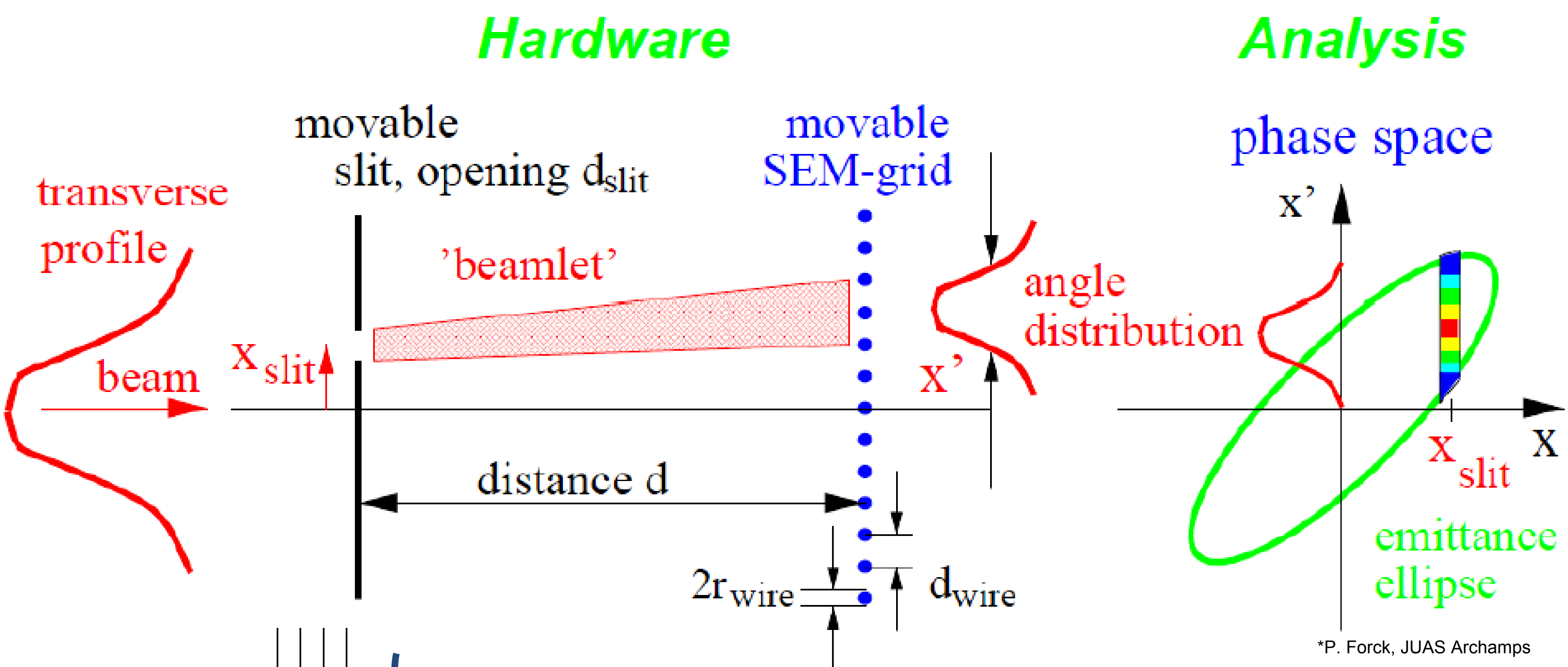
A coupling parameter t is introduced to quantify the inter-plane coupling and defined as:

$$t = \frac{\varepsilon_x \varepsilon_y}{\varepsilon_1 \varepsilon_2} - 1 \geq 0,$$

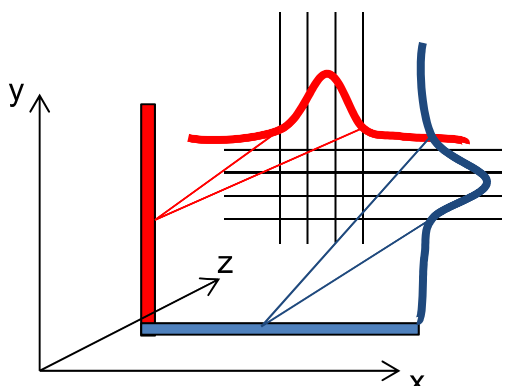
In other words ε_1 and ε_2 are the rms-emittaces of a fully decoupled beam.

or in simple words: uncoupled beams are an idealization to simplify the beam dynamics and are a best case scenario. If the beam is correlated the projected emittance is larger than necessary and could be decreased!

Emittance measurements:
Slit-grid (concept)



*P. Forck, JUAS Archamps



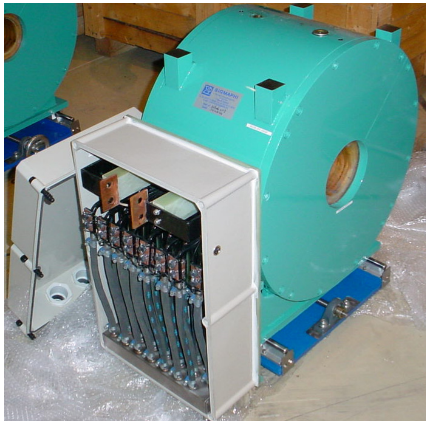
A slit-grid emittance measurement in one plane is always integrating over the other plane

Motivation:
Envelopes along Solenoid Channel

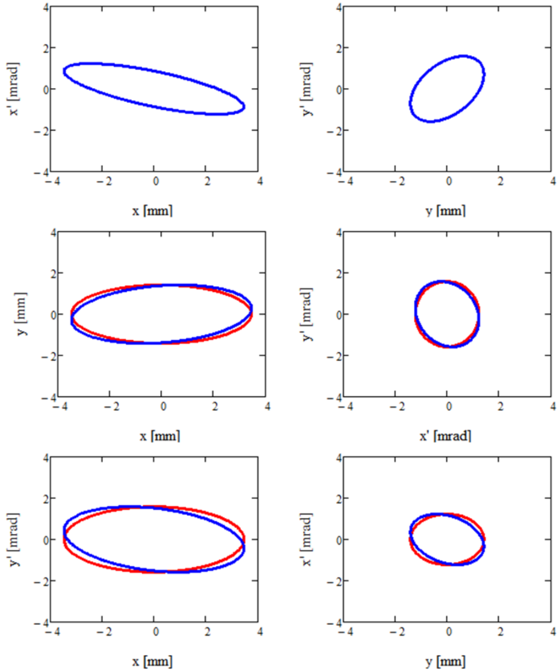
initial beam:

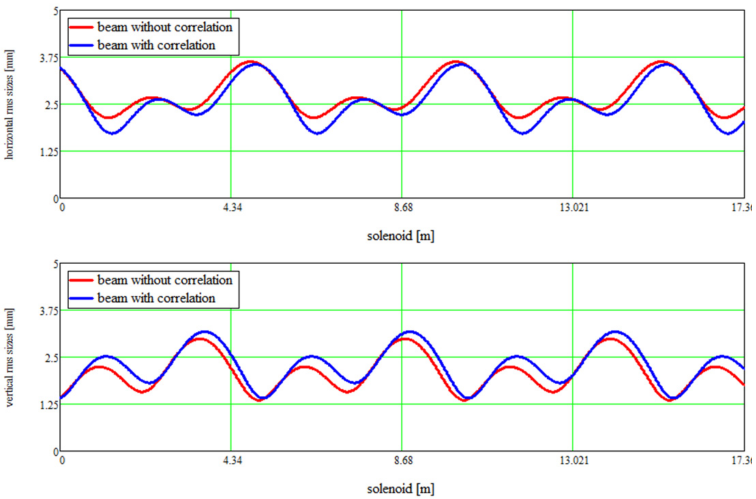
$$C_1=\begin{bmatrix} 12.00 & -3.00 & 0.00 & 0.00 \\ -3.00 & 1.50 & 0.00 & 0.00 \\ 0.00 & 0.00 & 2.00 & 1.00 \\ 0.00 & 0.00 & 1.00 & 2.50 \end{bmatrix}$$ uncorrelated

$$C_2=\begin{bmatrix} 12.00 & -3.00 & 1 & -1.5 \\ -3.00 & 1.50 & -0.5 & -0.35 \\ 1.00 & -0.50 & 2.00 & 1.00 \\ -1.50 & -0.35 & 1.00 & 2.50 \end{bmatrix}$$ correlated

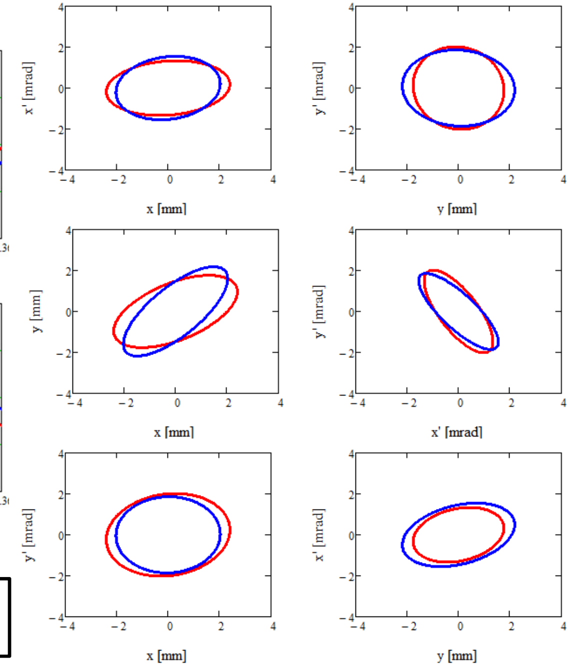


$$M_{sol} = \begin{bmatrix} C^2 & \frac{SC}{K} & SC & \frac{S^2}{K} \\ -KSC & C^2 & -KS^2 & CS \\ -SC & -\frac{S^2}{K} & C^2 & \frac{SC}{K} \\ KS^2 & -SC & -KSC & C^2 \end{bmatrix}$$



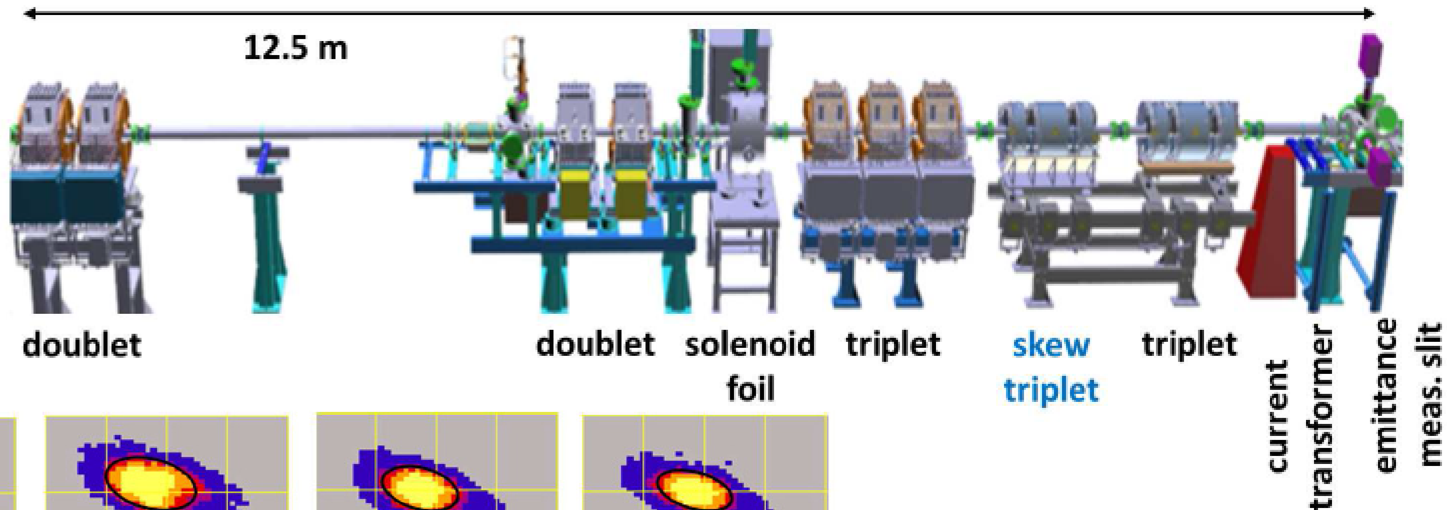


final beam:



red and blue envelopes differ

Motivation:
EMTEX



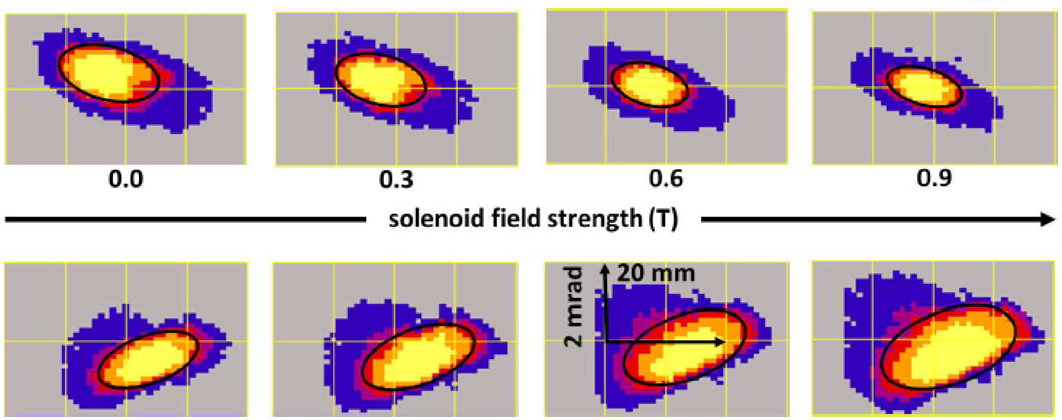
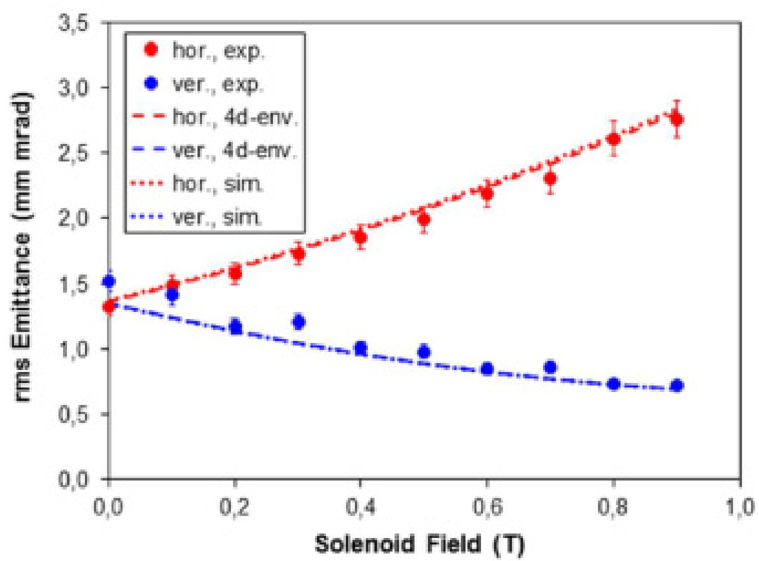


FIG. 4. (color online) Vertical (upper) and horizontal (lower) phase space distributions measured at the exit of the EMTEX beam line as functions of the solenoid field strength. All other settings were kept constant. Black ellipses indicate the 4×rms ellipses.

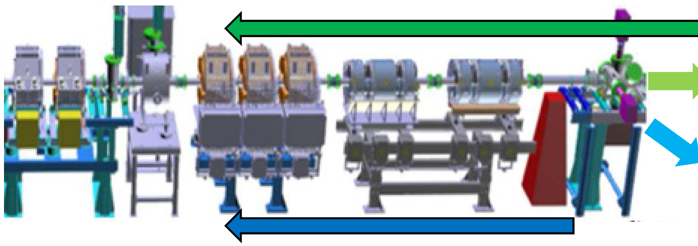


Physical Review Letters, 113, (2014) 264802

Experimental results
skew method

Emittance measurements on a 1.7mA $^{238}U^{28+}$ beam behind the skew quadrupole of EMTEX have been used to measure the 4D emittance. The emittance measurement without using the skew quadrupole **assuming an uncorrelated beam** at the entrance of EMTEX results in the second-moment beam matrix**:**

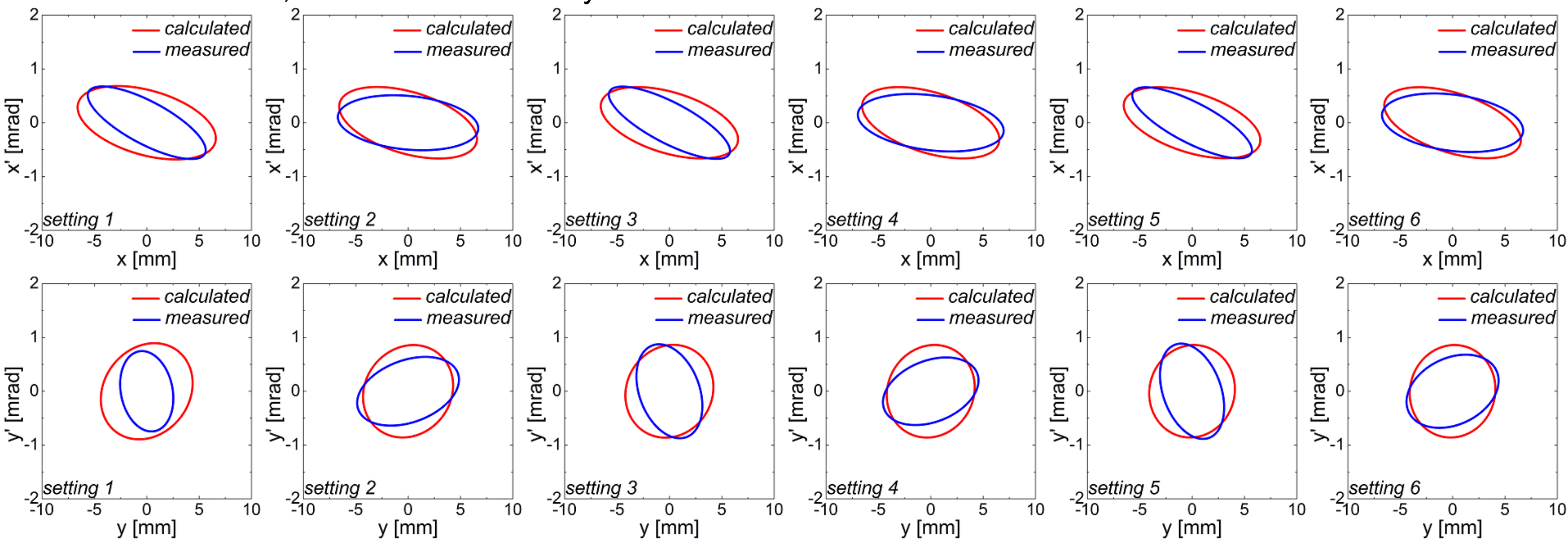
$$C_0 = \begin{pmatrix} 12.79 & 1.89 & 0 & 0 \\ 1.89 & 0.62 & 0 & 0 \\ 0 & 0 & 32.18 & 3.49 \\ 0 & 0 & 3.49 & 0.46 \end{pmatrix}$$



α_x = -0.902, α_y = -2.160
β_x = 6.11, β_y = 19.89 m/rad
ε_x = 2.1, ε_y = 1.6 *mm*mrad*

setting 1–6

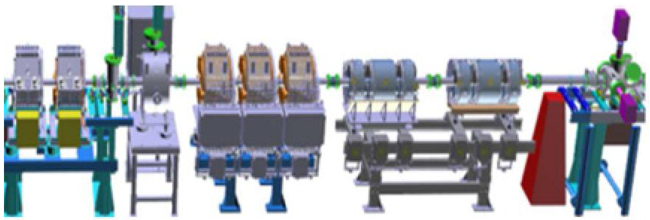
Repeating the measurements for turned on skews and comparing them to the simulations, using the above uncorrelated matrix, does not fit sufficiently well! Thus it is concluded the initial beam inhabits correlations.



Experimental results
skew method

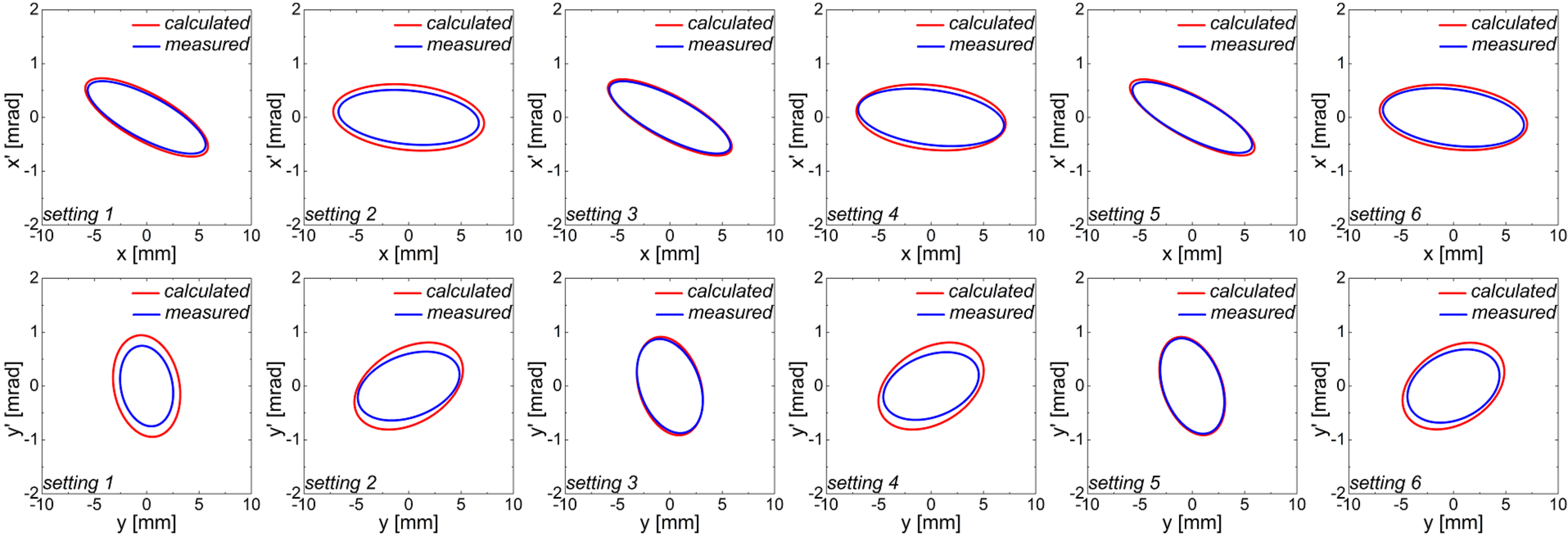
A method has been developed to determine the coupling moments. The resulting second-moment beam matrix at the entrance is:

$$C'_0 = \begin{pmatrix} 12.79 & 1.89 & 0.18 & 0.37 \\ 1.89 & 0.62 & 1.69 & 0.29 \\ 0.18 & 1.69 & 32.18 & 3.49 \\ 0.37 & 0.29 & 3.49 & 0.46 \end{pmatrix}$$



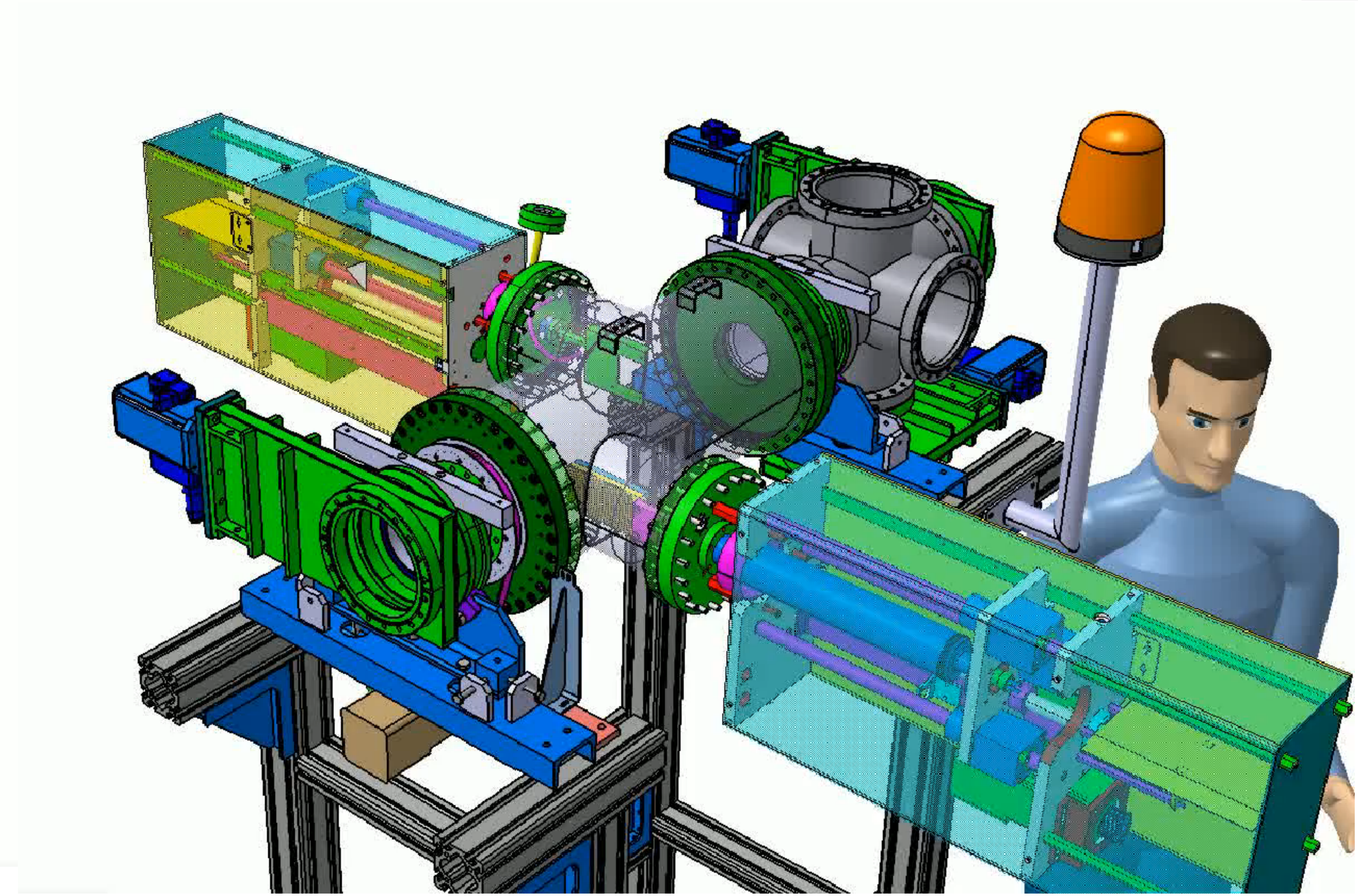
ε_1 = 2.1, ε_2 = 1.2 *mm*mrad*
coupling parameter t = 0.342

To our knowledge this is the first successful measurement of the 4D-rms-emittance of ions ≥ 150 keV/u.
In this example removing the correlation would allow for an increase of the beam brilliance by 75%.



NIMA 2016, doi: 10.1016/j.nima.2016.02.090

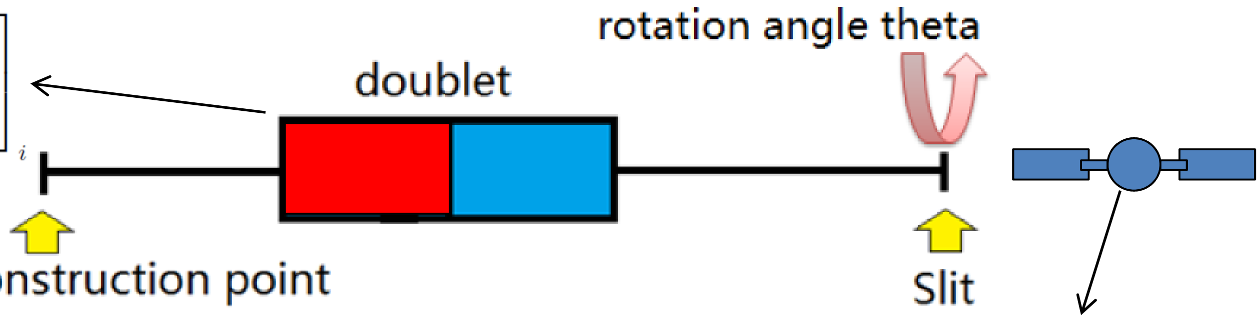
ROSE
Instead of rotating the beam



ROSE*
working principle**

$$\begin{bmatrix} x \\ x' \\ y \\ y' \end{bmatrix}_f^a = \begin{bmatrix} m_{11}^a & m_{12}^a & 0 & 0 \\ m_{21}^a & m_{22}^a & 0 & 0 \\ 0 & 0 & m_{33}^a & m_{34}^a \\ 0 & 0 & m_{43}^a & m_{44}^a \end{bmatrix} \begin{bmatrix} x \\ x' \\ y \\ y' \end{bmatrix}_i$$

transfer matrix M
from position i to position f for a magnetic field setting a or b



$$C_f = \begin{bmatrix} \langle xx \rangle & \langle xx' \rangle & \langle xy \rangle & \langle xy' \rangle \\ \langle x'x \rangle & \langle x'x' \rangle & \langle x'y \rangle & \langle x'y' \rangle \\ \langle yx \rangle & \langle yx' \rangle & \langle yy \rangle & \langle yy' \rangle \\ \langle y'x \rangle & \langle y'x' \rangle & \langle y'y \rangle & \langle y'y' \rangle \end{bmatrix}$$

$$\begin{bmatrix} x \\ x' \\ y \\ y' \end{bmatrix}_\theta^a = \begin{bmatrix} cos\theta & 0 & sin\theta & 0 \\ 0 & cos\theta & 0 & sin\theta \\ -sin\theta & 0 & cos\theta & 0 \\ 0 & -sin\theta & 0 & cos\theta \end{bmatrix} \begin{bmatrix} x \\ x' \\ y \\ y' \end{bmatrix}_f^a$$

rotation matrix M_θ
rotation of whole accelerator (beam) or emittance scanner is equal

* Deutsche Patentanmeldung Nr. 102015118017.0 Drehmodul für eine Beschleunigeranlage
** Phys. Rev. ST Accel. Beams 16, 044201 (2013).

ROSE*

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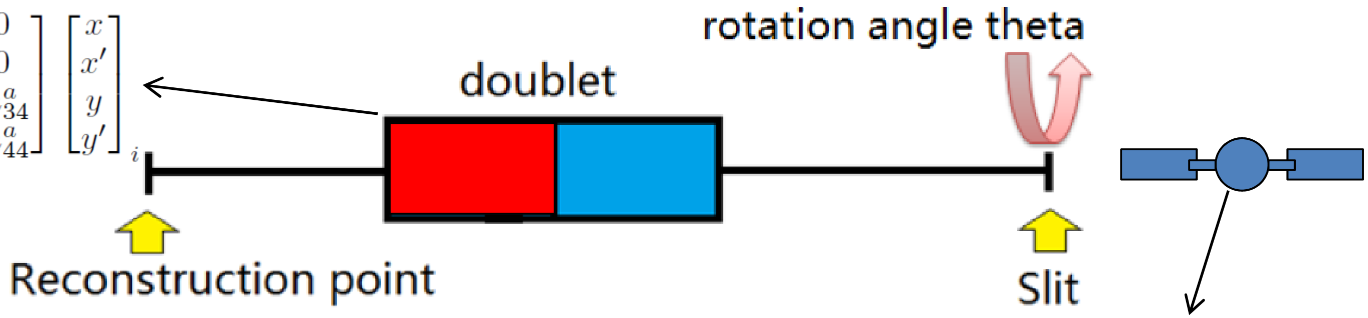

$$\begin{bmatrix} x \\ x' \\ y \\ y' \end{bmatrix}_\theta^a = \begin{bmatrix} cos\theta & 0 & sin\theta & 0 \\ 0 & cos\theta & 0 & sin\theta \\ -sin\theta & 0 & cos\theta & 0 \\ 0 & -sin\theta & 0 & cos\theta \end{bmatrix} \begin{bmatrix} x \\ x' \\ y \\ y' \end{bmatrix}_f^a$$

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$$C_f = \begin{bmatrix} \langle xx \rangle & \langle xx' \rangle & \langle xy \rangle & \langle xy' \rangle \\ \langle x'x \rangle & \langle x'x' \rangle & \langle x'y \rangle & \langle x'y' \rangle \\ \langle yx \rangle & \langle yx' \rangle & \langle yy \rangle & \langle yy' \rangle \\ \langle y'x \rangle & \langle y'x' \rangle & \langle y'y \rangle & \langle y'y' \rangle \end{bmatrix}$$

All values are measured using ROSE at the final position. Knowing the transfer and rotation matrix they can be calculated back to the reconstruction point, the initial position of the original not changing beam matrix C_i. 100% transmission between initial and final Position is of course required for all settings.

1. **θ=0°** magnet setting **a** delivers $\langle xx \rangle_f^a$, $\langle xx' \rangle_f^a$, $\langle x'x' \rangle_f^a$

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transfer matrix M

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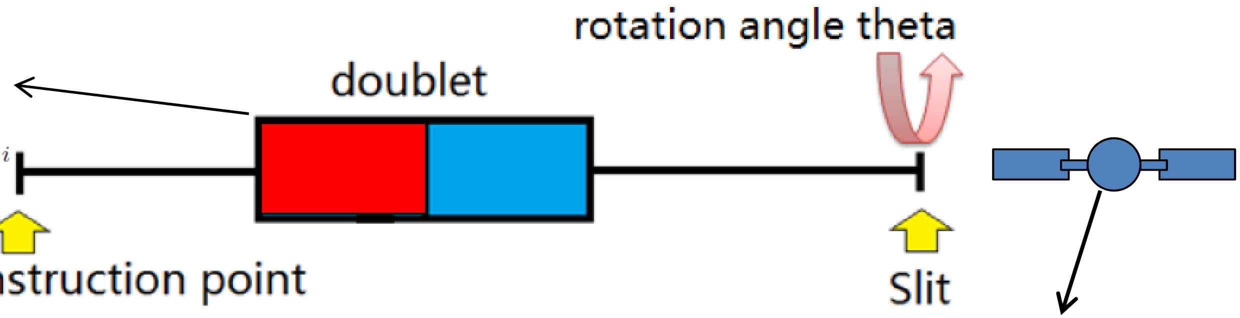

$$\begin{bmatrix}x\\x'\\y\\y'\end{bmatrix}_\theta^a = \begin{bmatrix} cos\theta & 0 & sin\theta & 0\\ 0 & cos\theta & 0 & sin\theta\\ -sin\theta & 0 & cos\theta & 0\\ 0 & -sin\theta & 0 & cos\theta\end{bmatrix}\begin{bmatrix}x\\x'\\y\\y'\end{bmatrix}_f^a$$

rotation matrix M_θ

rotation of whole accelerator (beam) or emittance scanner is equal

$$C_f = \begin{bmatrix} \langle xx\rangle & \langle xx'\rangle & \langle xy\rangle & \langle xy'\rangle\\ \langle x'x\rangle & \langle x'x'\rangle & \langle x'y\rangle & \langle x'y'\rangle\\ \langle yx\rangle & \langle yx'\rangle & \langle yy\rangle & \langle yy'\rangle\\ \langle y'x\rangle & \langle y'x'\rangle & \langle y'y\rangle & \langle y'y'\rangle \end{bmatrix}$$

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2. **θ=90°** magnet setting **a** delivers $\langle yy\rangle_f^a$, $\langle yy'\rangle_f^a$, $\langle y'y'\rangle_f^a$

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transfer matrix M

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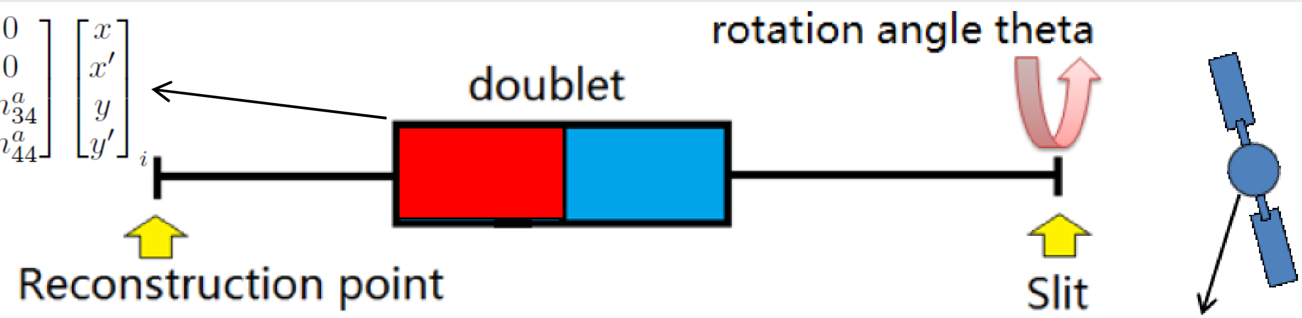

$$\begin{bmatrix} x \\ x' \\ y \\ y' \end{bmatrix}_\theta^a = \begin{bmatrix} cos\theta & 0 & sin\theta & 0 \\ 0 & cos\theta & 0 & sin\theta \\ -sin\theta & 0 & cos\theta & 0 \\ 0 & -sin\theta & 0 & cos\theta \end{bmatrix} \begin{bmatrix} x \\ x' \\ y \\ y' \end{bmatrix}_f^a$$

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2. **θ=90°** magnet setting **a** delivers $<yy>_f^a$, $<yy'>_f^a$, $<y'y'>_f^a$
3. **θ=45°** magnet setting **a** delivers $<yy>_\theta^a$, $<yy'>_\theta^a$, $<y'y'>_\theta^a$

* Deutsche Patentanmeldung Nr. 102015118017.0 Drehmodul für eine Beschleunigeranlage

** Phys. Rev. ST Accel. Beams 16, 044201 (2013).

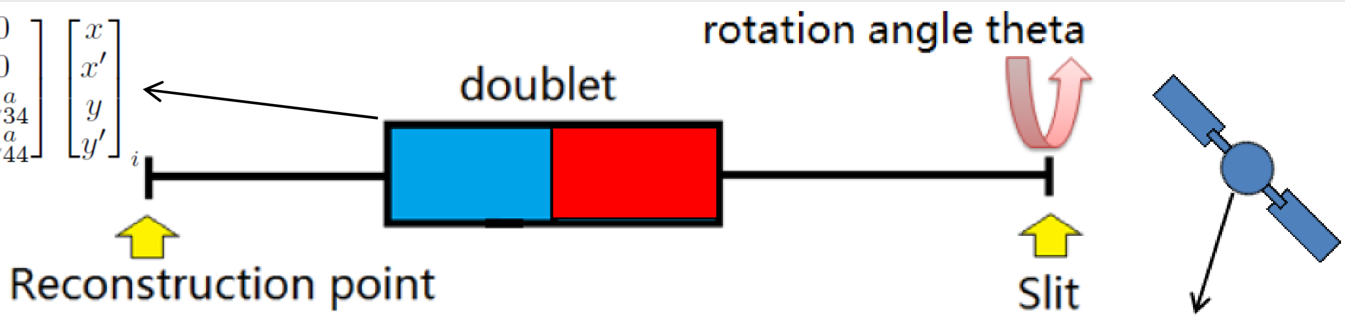
ROSE*

working principle**

$$\begin{bmatrix} x \\ x' \\ y \\ y' \end{bmatrix}_f^a = \begin{bmatrix} m_{11}^a & m_{12}^a & 0 & 0 \\ m_{21}^a & m_{22}^a & 0 & 0 \\ 0 & 0 & m_{33}^a & m_{34}^a \\ 0 & 0 & m_{43}^a & m_{44}^a \end{bmatrix} \begin{bmatrix} x \\ x' \\ y \\ y' \end{bmatrix}_i$$

transfer matrix M

from position i to position f for a magnetic field setting a or b



$$C_{f\text{->}i} = \begin{bmatrix} \langle xx \rangle & \langle xx' \rangle & \langle xy \rangle + & \langle xy' \rangle \\ \langle x'x \rangle & \langle x'x' \rangle & \langle x'y \rangle & \langle x'y' \rangle \\ \langle yx \rangle + & \langle yx' \rangle & \langle yy \rangle & \langle yy' \rangle \\ \langle y'x \rangle & \langle y'x' \rangle & \langle y'y \rangle & \langle y'y' \rangle \end{bmatrix}$$

$$\begin{bmatrix} x \\ x' \\ y \\ y' \end{bmatrix}_\theta^a = \begin{bmatrix} cos\theta & 0 & sin\theta & 0 \\ 0 & cos\theta & 0 & sin\theta \\ -sin\theta & 0 & cos\theta & 0 \\ 0 & -sin\theta & 0 & cos\theta \end{bmatrix} \begin{bmatrix} x \\ x' \\ y \\ y' \end{bmatrix}_f^a$$

rotation matrix M_θ

rotation of whole accelerator (beam) or emittance scanner is equal

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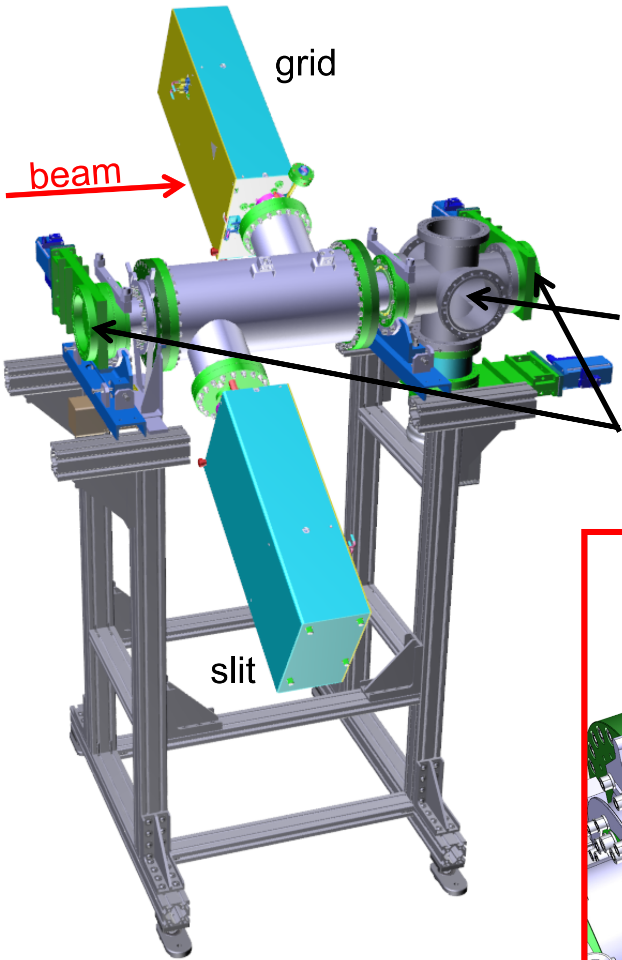
3. **θ=45°** magnet setting **a** delivers $\langle yy\rangle_\theta^a$, $\langle yy'\rangle_\theta^a$, $\langle y'y'\rangle_\theta^a$
4. **θ=45°** magnet setting **b** delivers $\langle xx\rangle_\theta^b$

only 4 measurements are needed to measure the full beam matrix

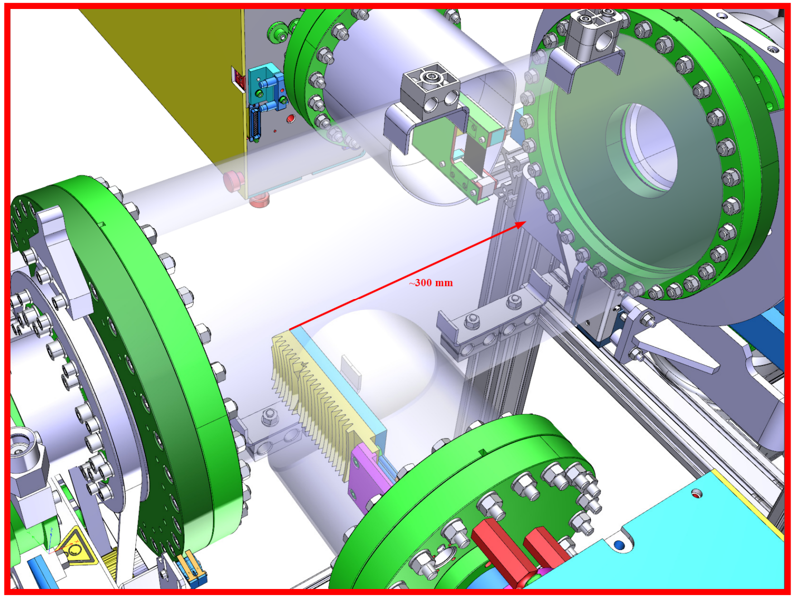
* Deutsche Patentanmeldung Nr. 102015118017.0 Drehmodul für eine Beschleunigeranlage

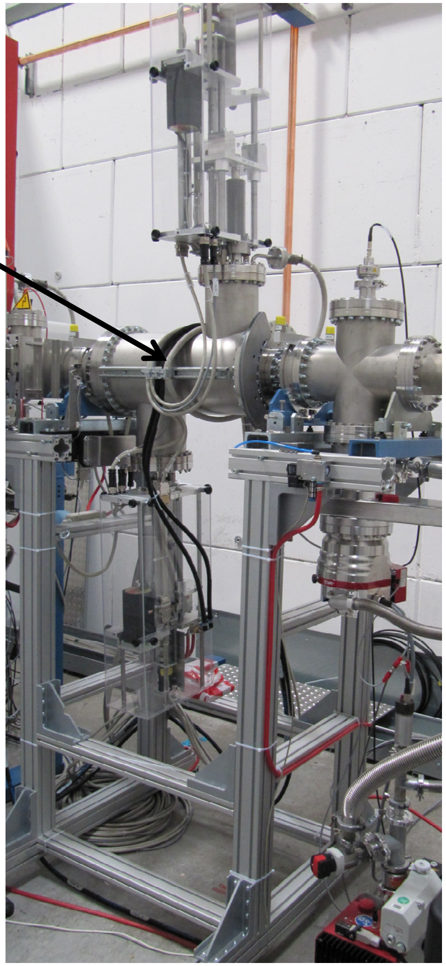
** Phys. Rev. ST Accel. Beams 16, 044201 (2013).

ROSE
Technical solutions



- slit & grid mounted on opposite sides to minimize torque
- cables wrapped around chamber
- fixed pumping chamber
- two gate valves



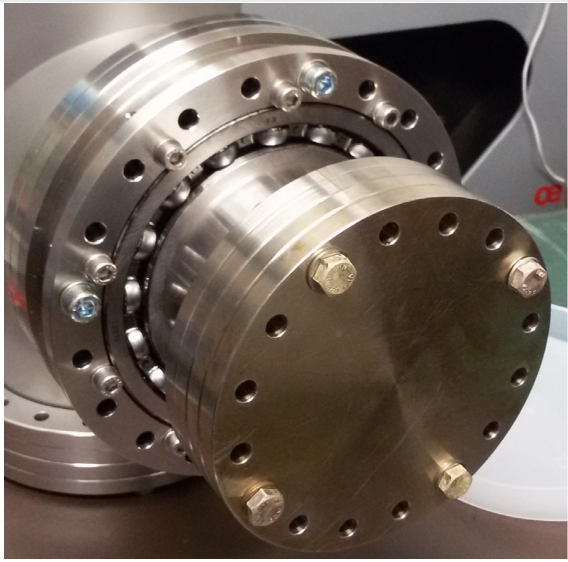


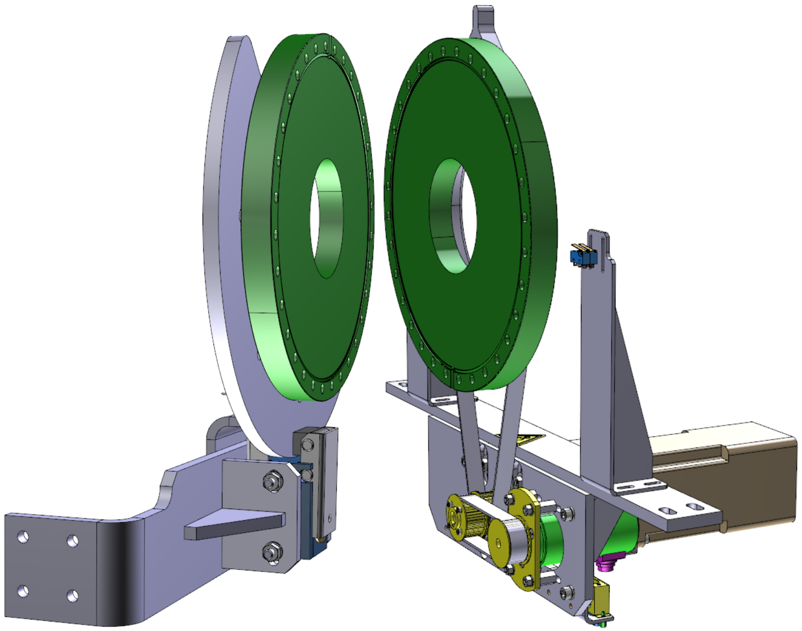
ROSE
Technical solutions

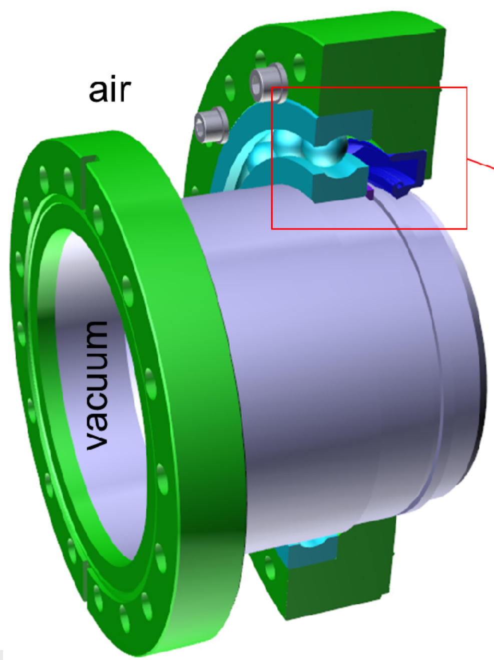
- end switches separated by 180°
- disk brake (closed during measurements)
- motor driver with belts ($\delta\theta \leq 0.5°$)
- 90° - rotation slowed activley to ≈ 30 sec

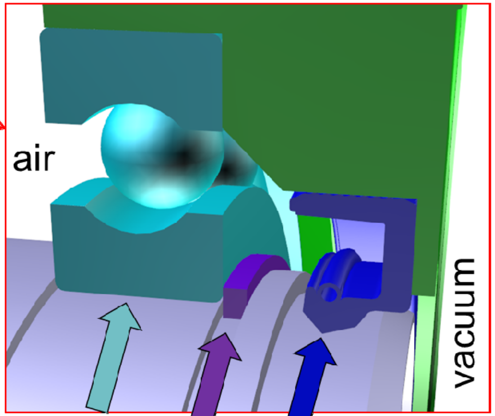
Vacuum issues:

- static pressure ≈ 5×10^{-8} mbar
- max. pressure during rotation ≈ 9×10^{-8} mbar
- recovery time ≈ 1 min

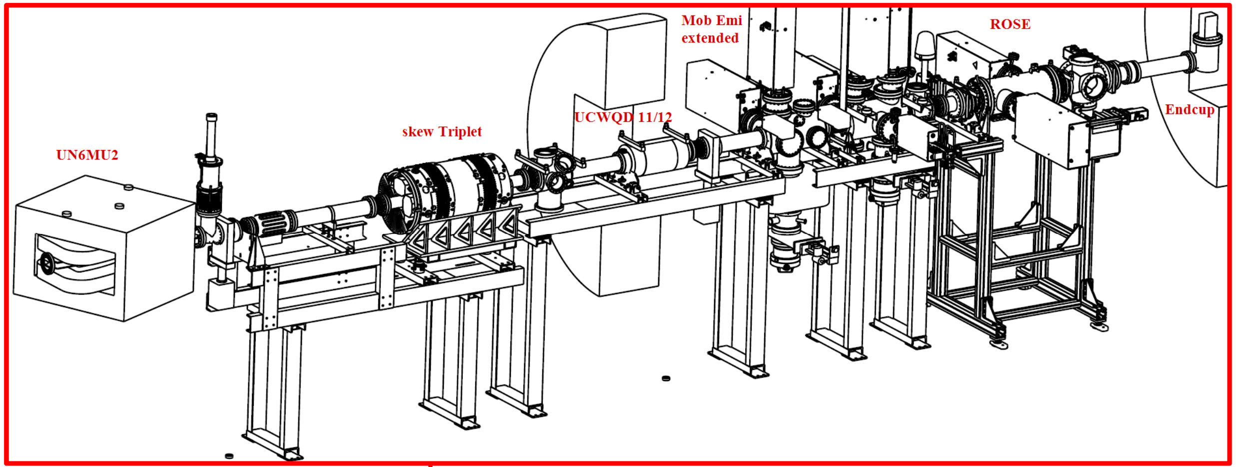




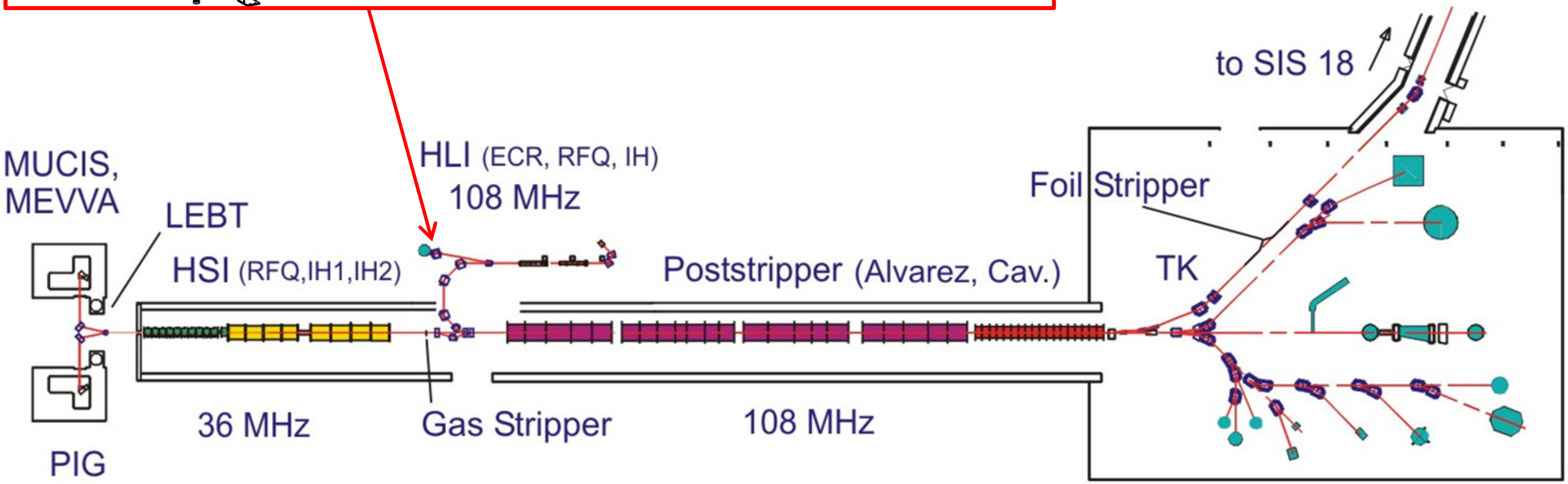




ROSE commissioning setup

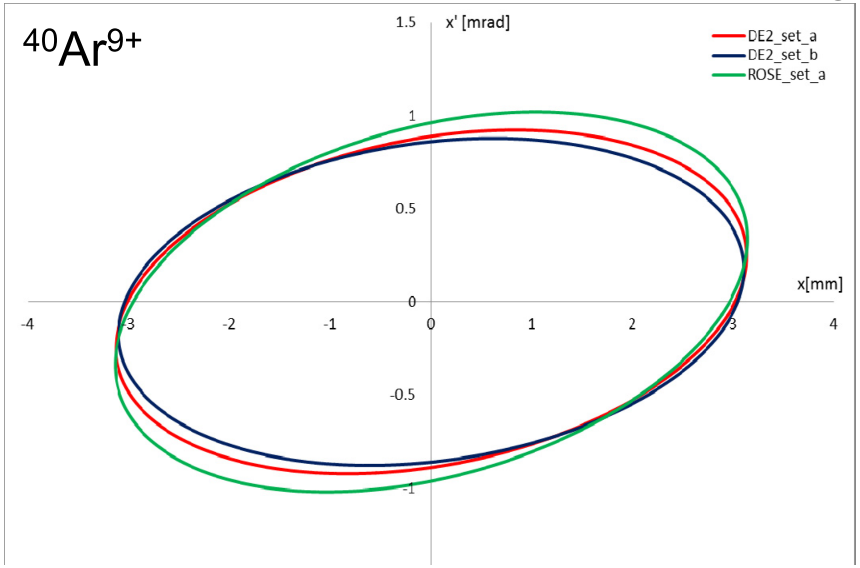


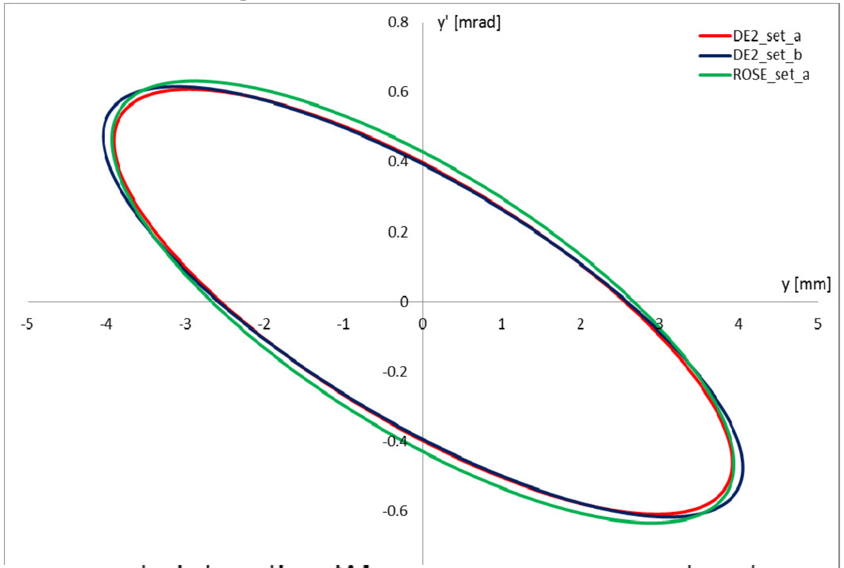
- measurements at exit of GSI's HLI
- 1.4 MeV/u of $^{40}Ar^{9+}$ and $^{83}Kr^{13+}$
- skew triplet to create x↔y correlations
- full transmission

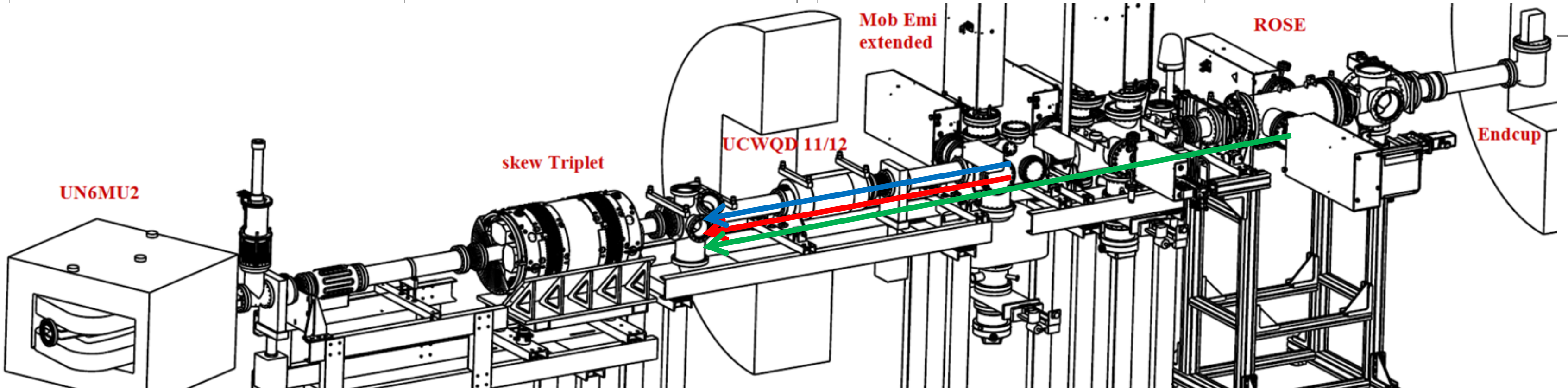


ROSE commissioning
Benchmarking

The first commissioning beam time mainly served to commission the hard- and software of ROSE and to benchmark it against existing emittance scanners.



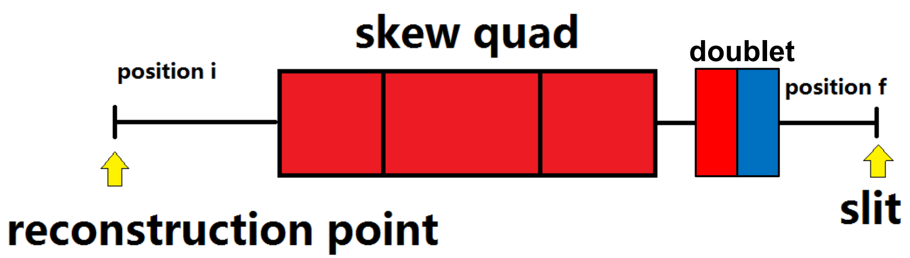


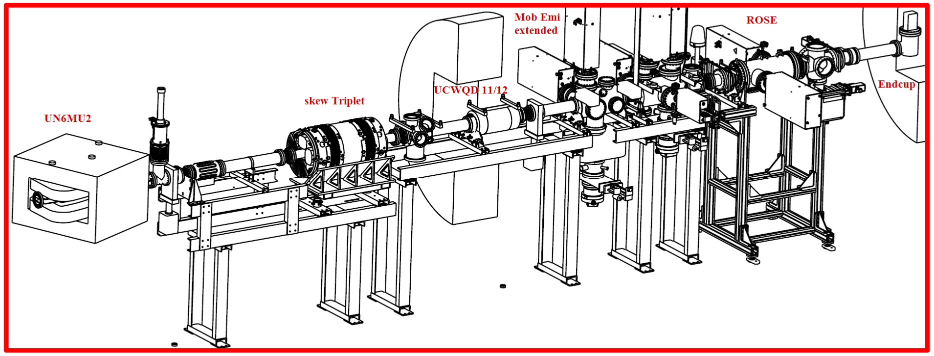


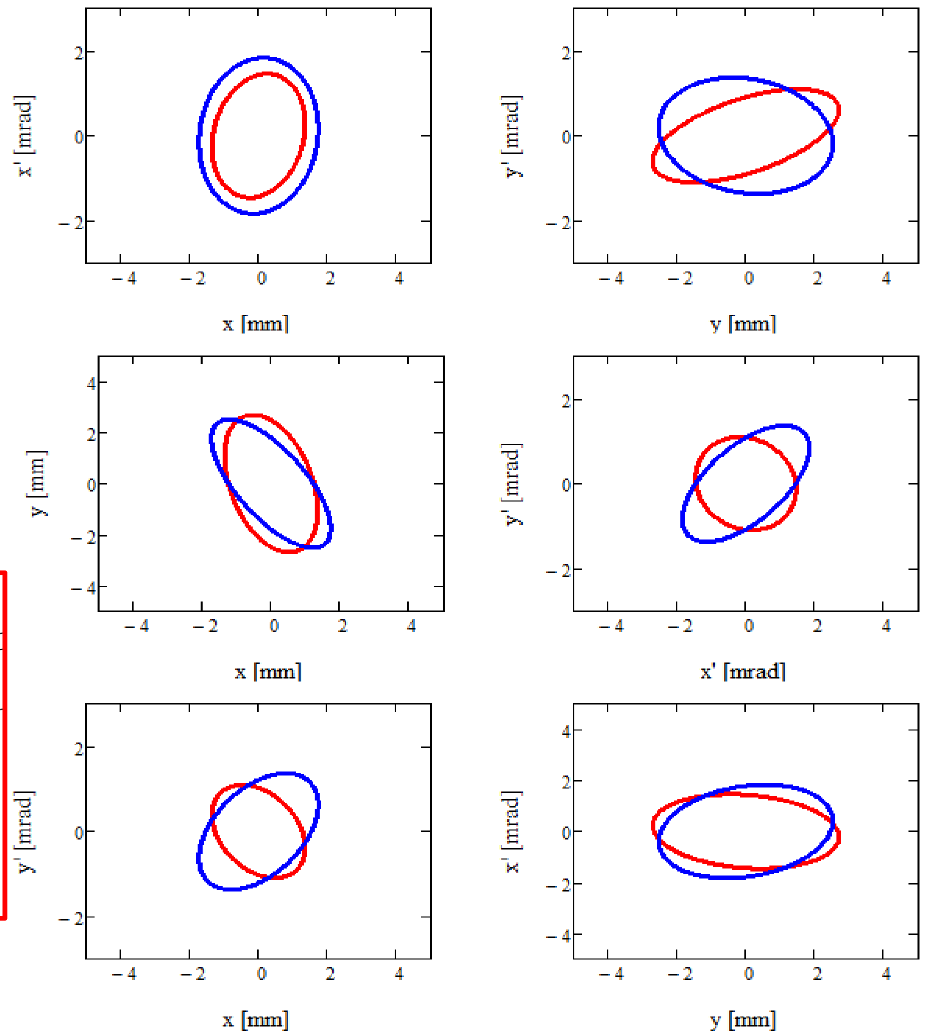
ROSE commissioning

4d emittance measurement of $^{83}Kr^{13+}$

Slit





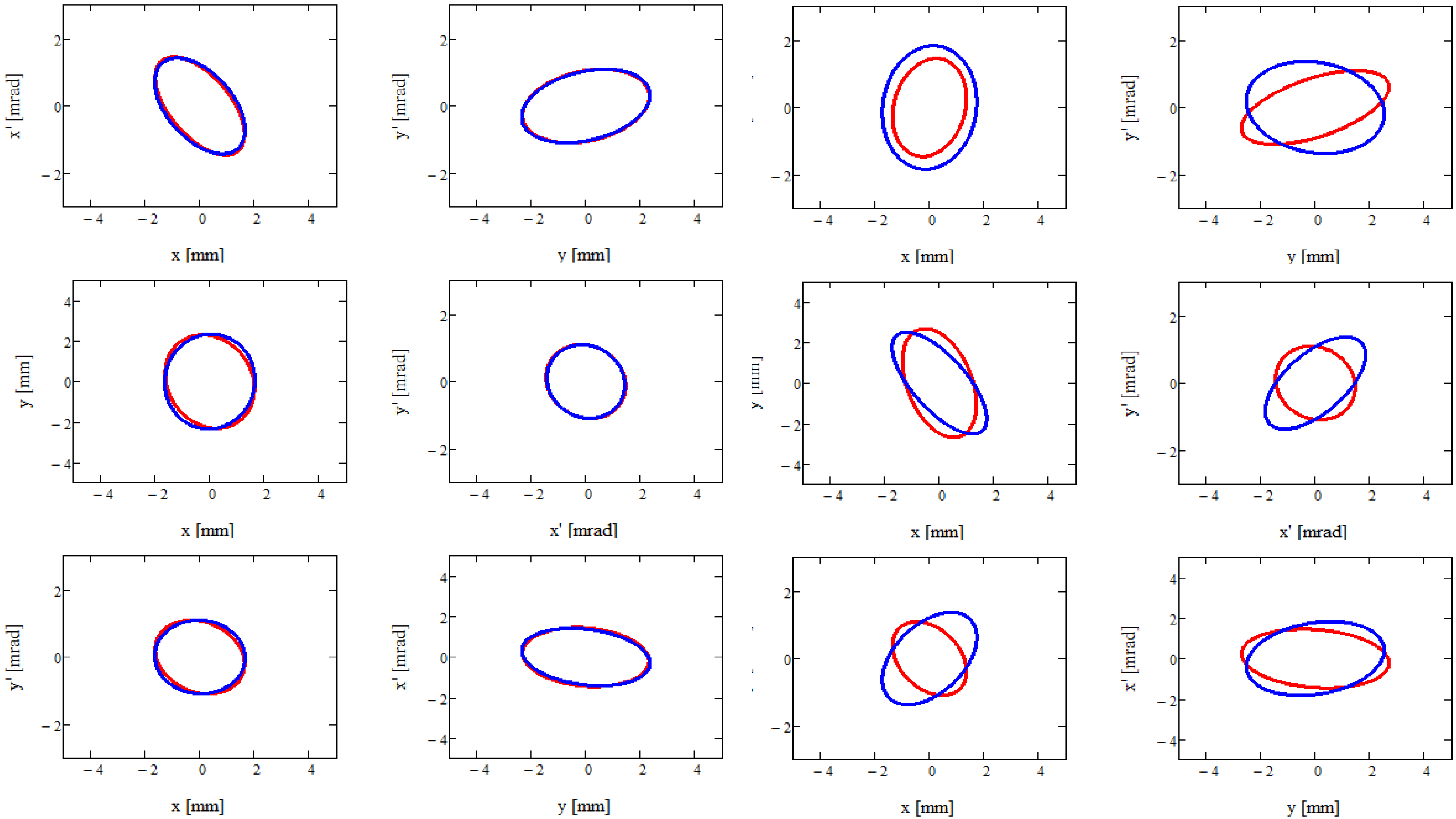


red skew off, **blue skew on**

ROSE commissioning

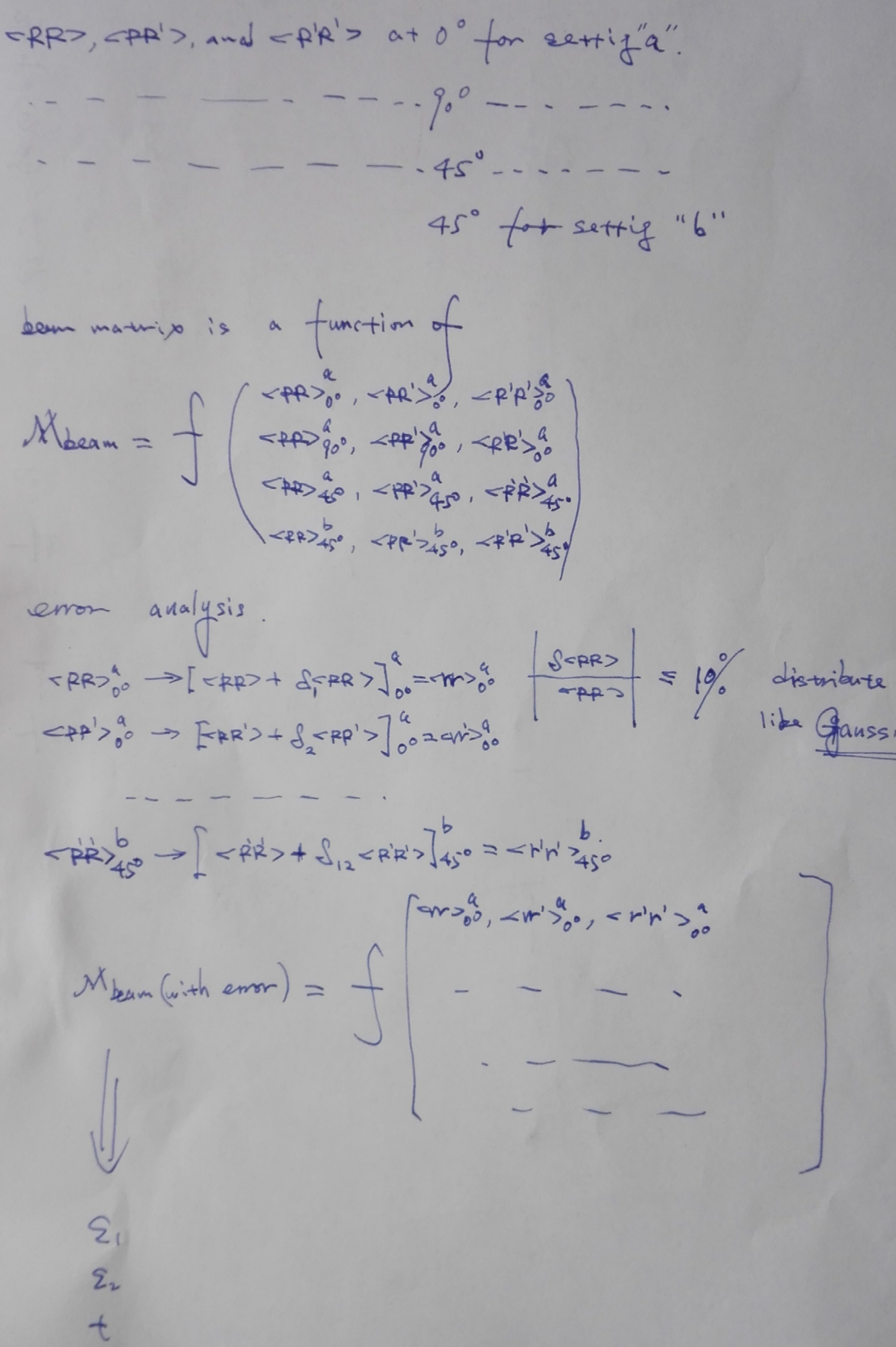
4d emittance measurement of $^{83}Kr^{13+}$

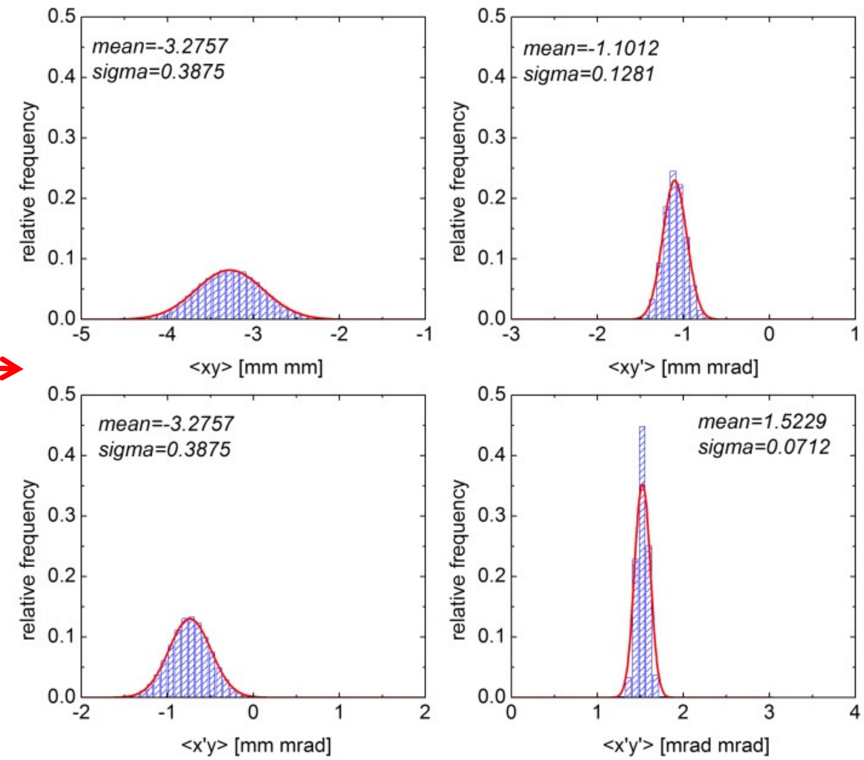
Reconstruction point in front of skew Slit



red skew off, blue skew on

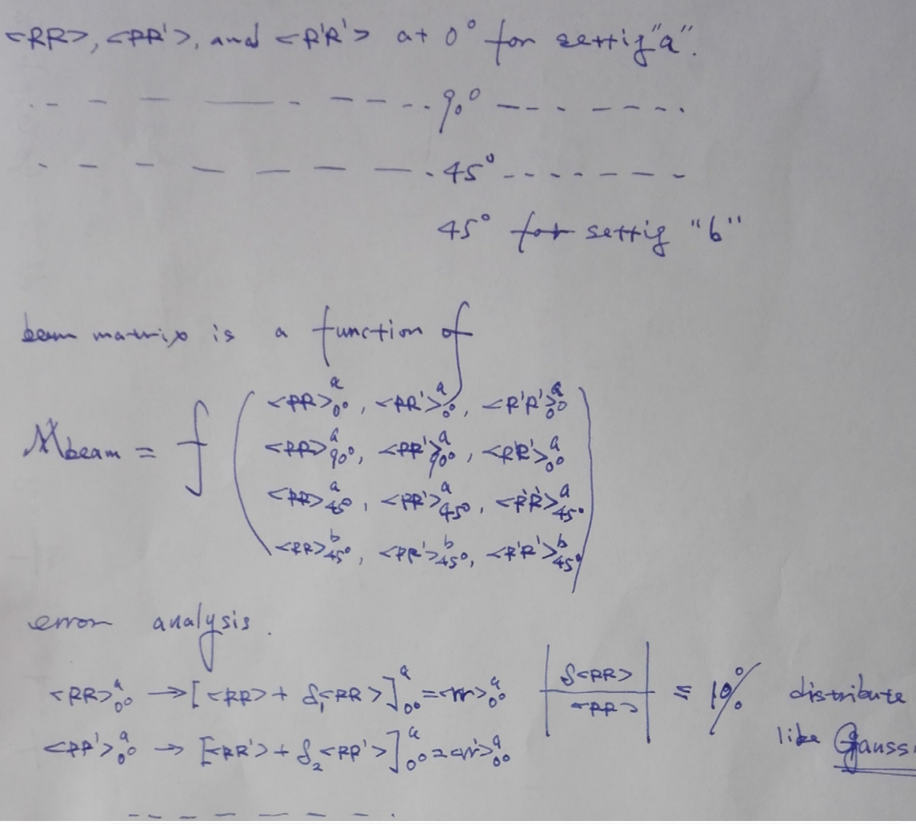
Error studies

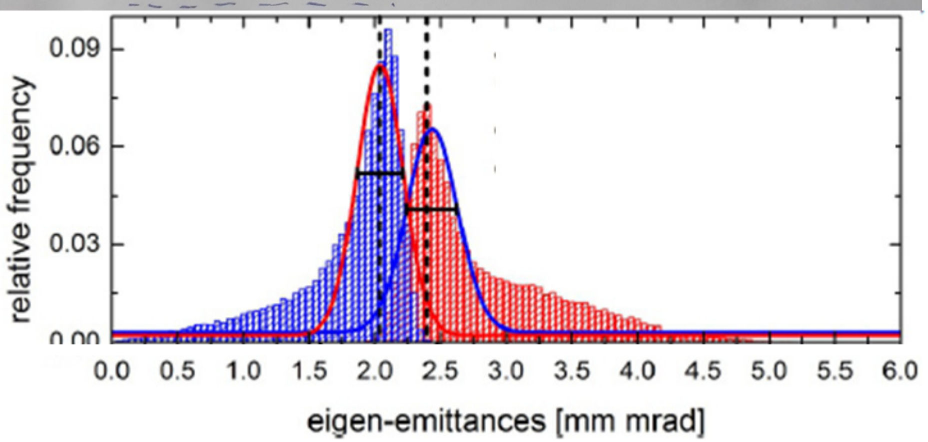




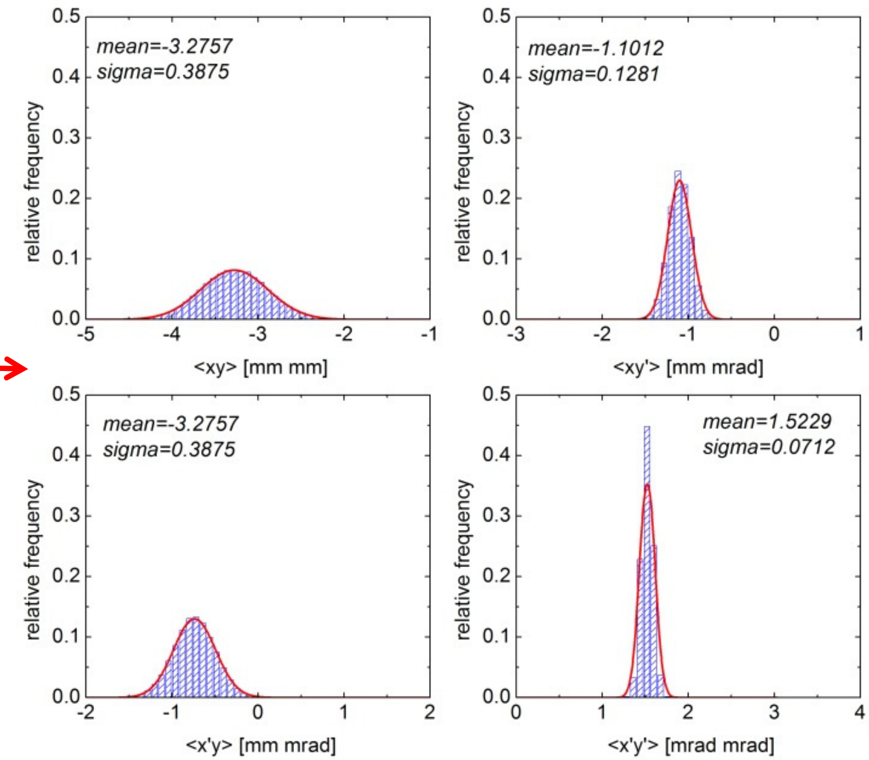
Each measured moment entering into the evaluation was varied randomly following a Gaussian distribution centered on its measured value

Error studies





From the measured moments derived Eigen-emittances of the HLI 1.4 MeV/u $^{83}Kr^{13+}$ beam.



Each measured moment entering into the evaluation was varied randomly following a Gaussian distribution centered on its measured value

Summary & Outlook

- We have measured the 4d beam parameters of a $^{238}U^{28+}$ beam with a kinetic energy of 11.4 MeV/u using the skew technique.
- We have developed and successfully commissioned ROSE, a prototype 4d emittance scanner that is independent of ion-species, -current and -energy.

- In the future we would like to
  - decouple the $^{238}U^{28+}$ beam using the skew triplet confirming it with ROSE
  - repeat EMTEX creating a flat beam accompanied by ROSE
  - build a two chamber system to gain flexibility and to reduce measurement time
  - And for curiosity we could use the skew to rotate the beam followed by a regular Quadrupole triplet to decouple the beam in its new coordinate system!

- With **NTG Neue Technologien GmbH & Co. KG** we have found an industrial partner. Together we are planning to develop a turnkey 4d emittance scanner for the ion accelerator community.


Thank you very much
for your attention