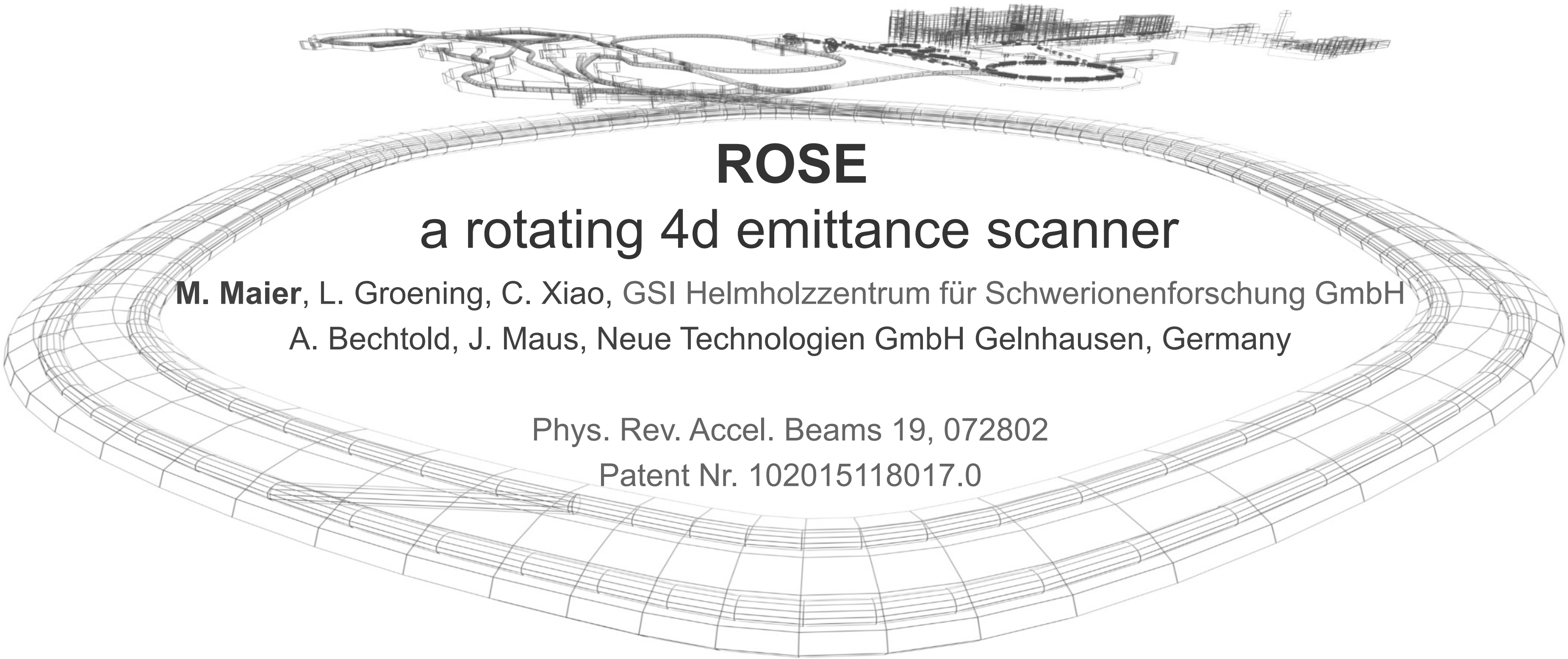
IBIC
MALMÖ, SWEDEN
International Beam Instrumentation Conference
8-12 SEPTEMBER 2019

FAIR GSI



ROSE
a rotating 4d emittance scanner

M. Maier, L. Groening, C. Xiao, GSI Helmholzzentrum für Schwerionenforschung GmbH
A. Bechtold, J. Maus, Neue Technologien GmbH Gelnhausen, Germany

Phys. Rev. Accel. Beams 19, 072802
Patent Nr. 102015118017.0

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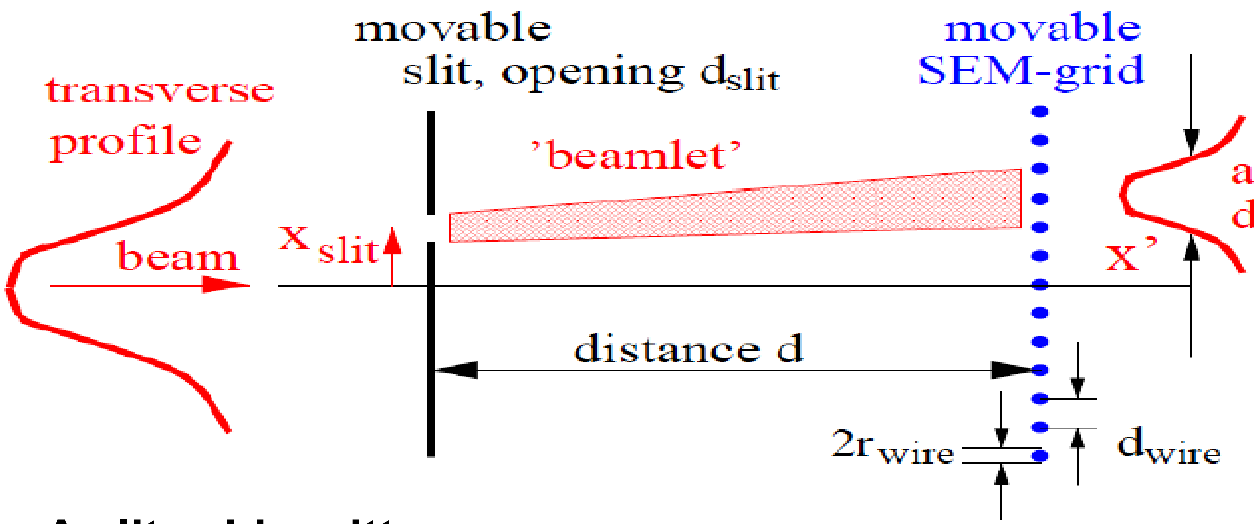
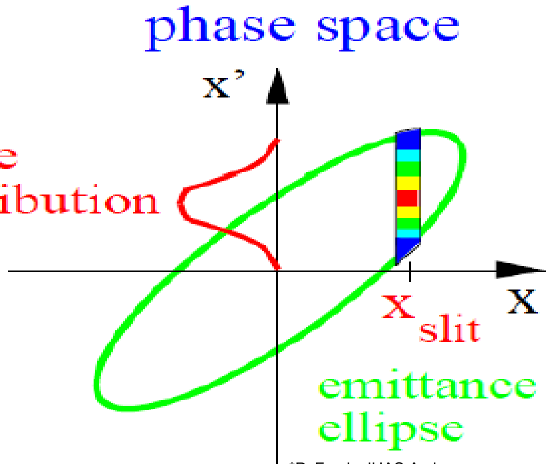
Introduction
slit grid emittance measurements

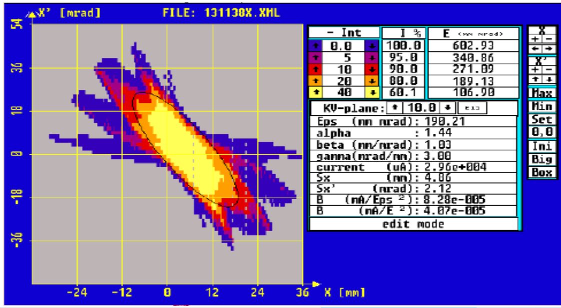
Hardware | **Analysis**





*P. Forck, JUAS Archamps

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

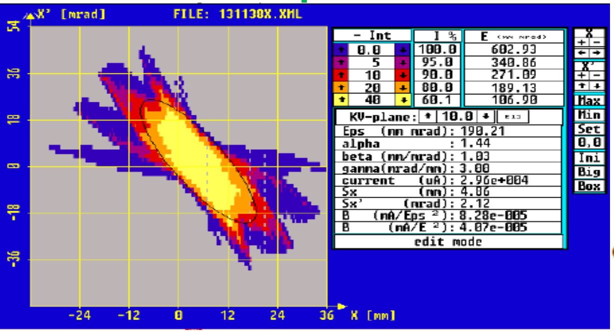


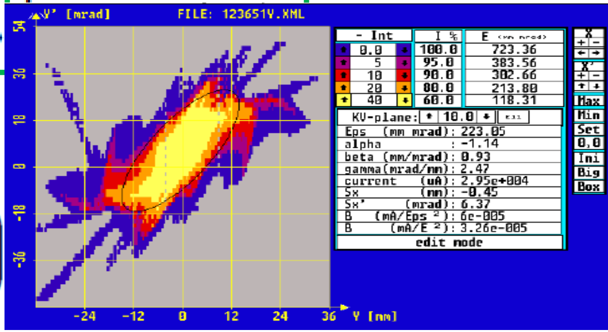
Introduction
The full 4 dimensional beam matrix

The four-dimensional symmetric beam matrix C:

For a decoupled beam the off-diagonal matrix elements (red) are zero.

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





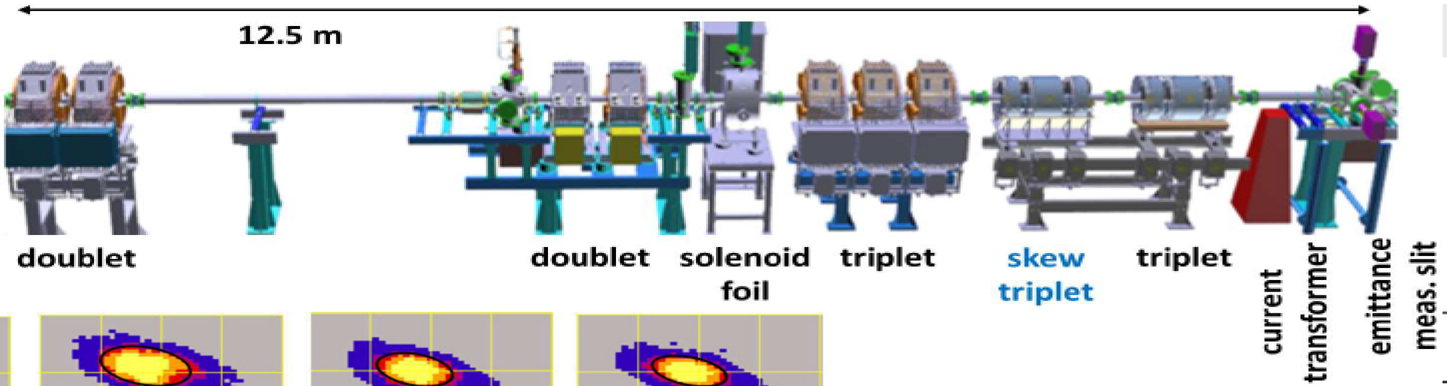
with $\varepsilon_x = \sqrt{(det\ \sigma_x)}$

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

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

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

Motivation: EMTEX
using coupled planes for emittance transfer



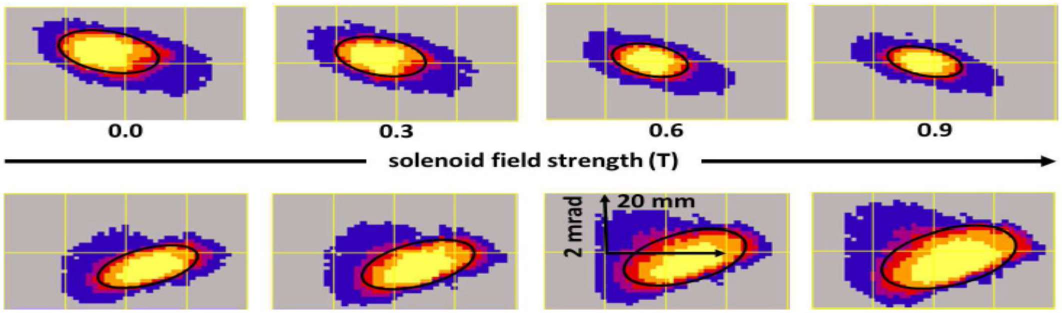
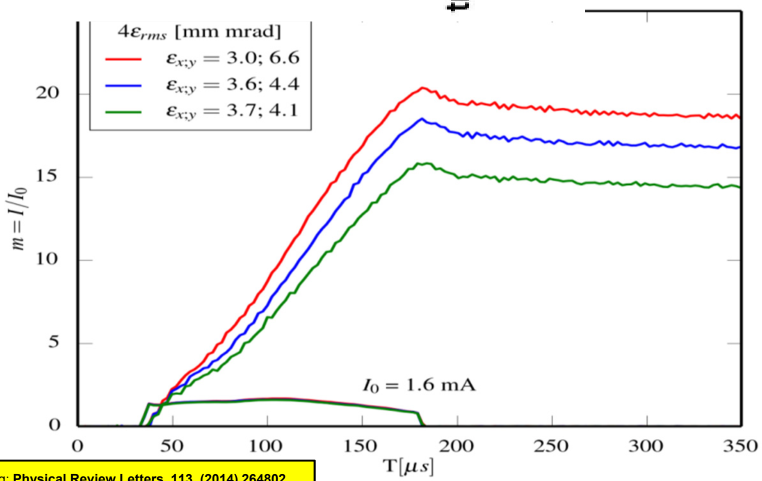


FIG. 4. (color online) Vertical (upper) and horizontal (lower) phase space distributions measured at the exit of the EMTEX beam line as functions of the solenoid field strength. All other settings were kept constant. Black ellipses indicate the 4×rms ellipses.



Experimental proof of adjustable single-knob ion beam emittance partitioning, L. Groening, M. Maier, C. Xiao, L. Dahl, P. Gerhard, O.K. Kester, S. Mickat, H. Vormann, and M. Vossberg: **Physical Review Letters, 113, (2014) 264802**

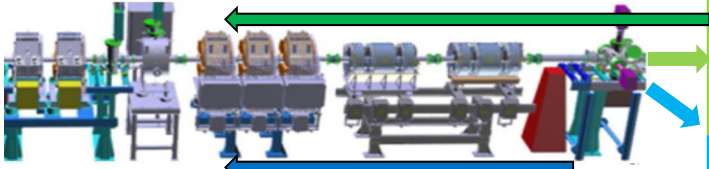
Injection optimization through generation of flat ion beams, S. Appel, L. Groening, Y. El Hayek, M. Maier, C. Xiao: **Nucl. Instr. and Meth. A 866, 36-39 (2017), DOI: 10.1016 / j.nima.2017.05.041**

ROSE – the idea

coupled Uranium beam for SIS18 injection

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**:**

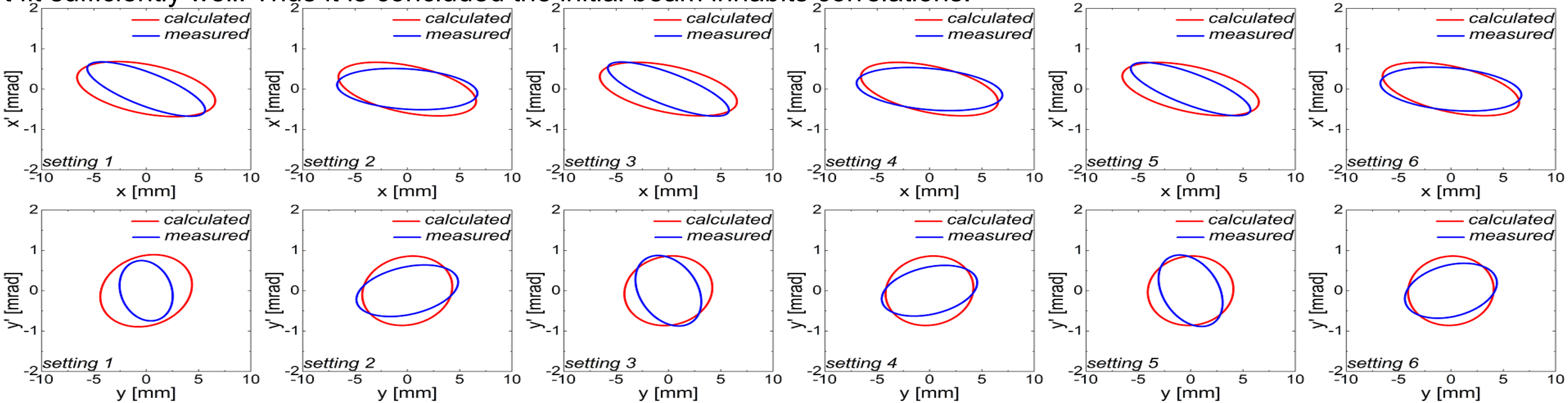
$$C_0 = \begin{pmatrix} 12.79 & 1.89 & 0 & 0 \\ 1.89 & 0.62 & 0 & 0 \\ 0 & 0 & 32.18 & 3.49 \\ 0 & 0 & 3.49 & 0.46 \end{pmatrix}$$



$\alpha_x = -0.902$, $\alpha_y = -2.160$
$\beta_x = 6.11$, $\beta_y = 19.89$ m/rad
$\varepsilon_x = 2.1$, $\varepsilon_y = 1.6$ *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.



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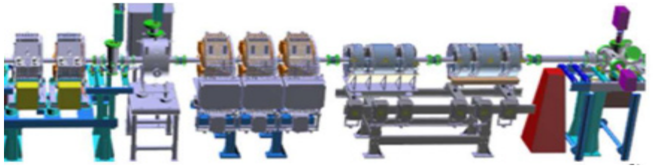
ROSE – the idea

coupled Uranium beam for SIS18 injection

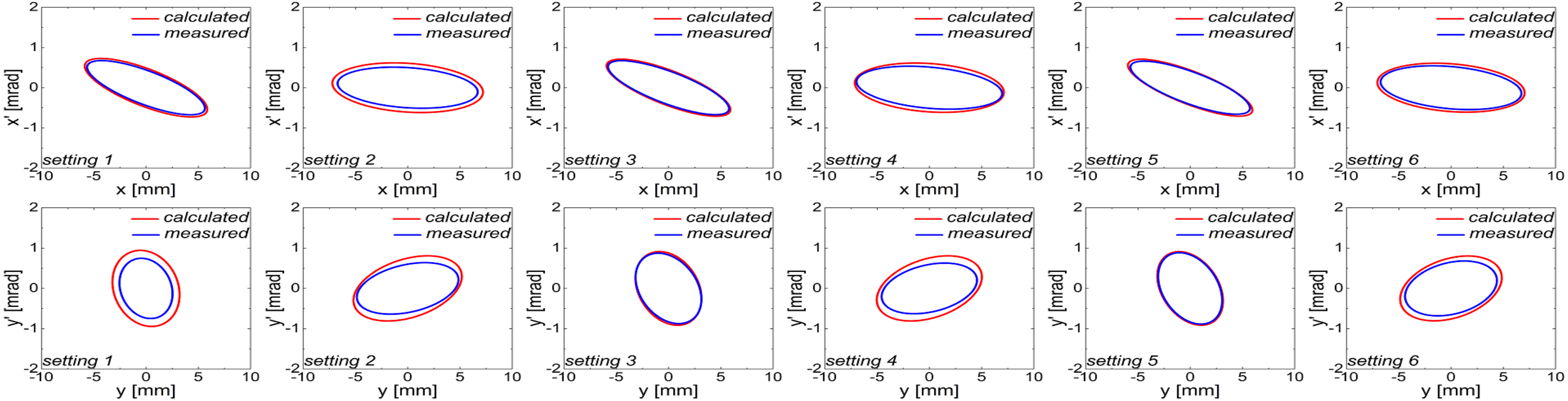
A mathematic method has been developed to determine the coupling moments. The resulting second-moment beam matrix at the entrance is:

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



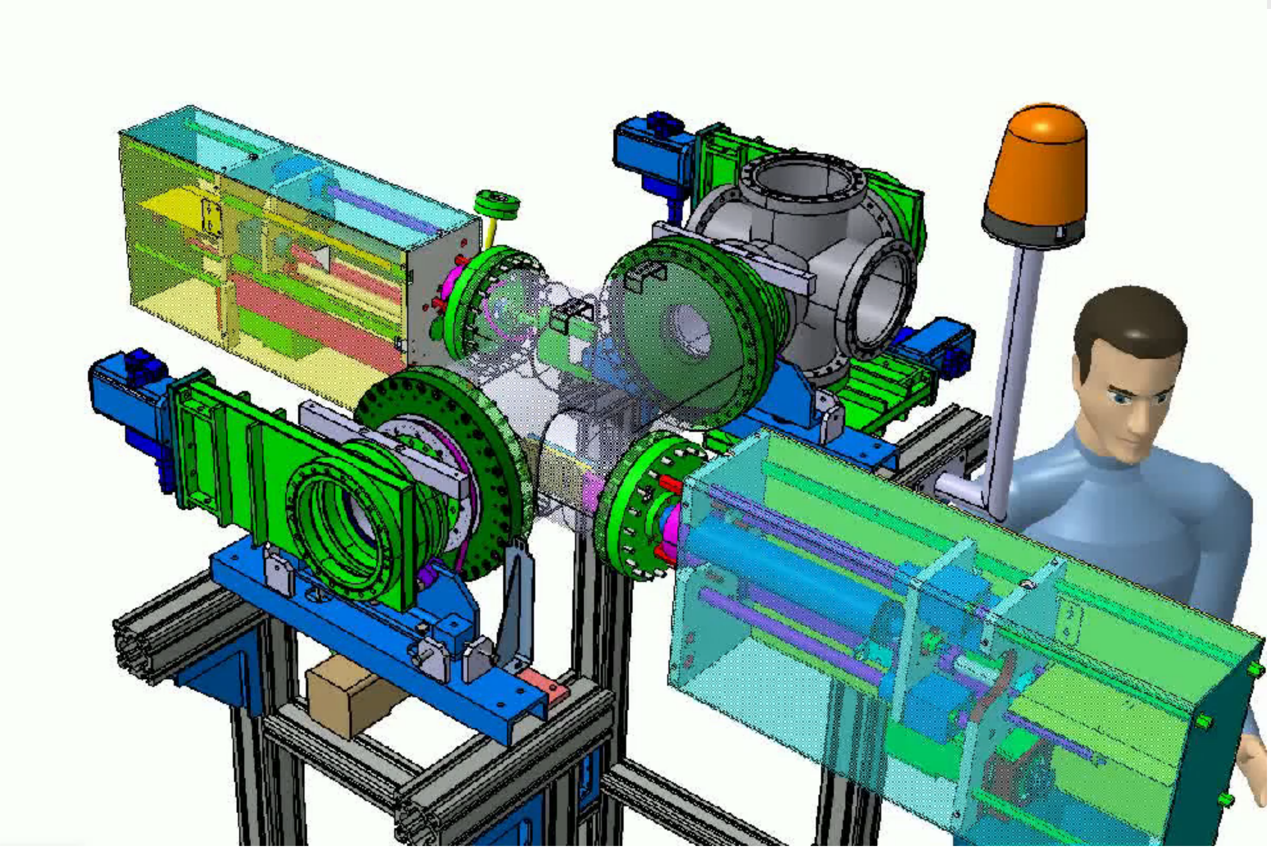
$\varepsilon_1 = 2.1$, $\varepsilon_2 = 1.2$ *mm*mrad*
coupling parameter t = 0.342

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%.

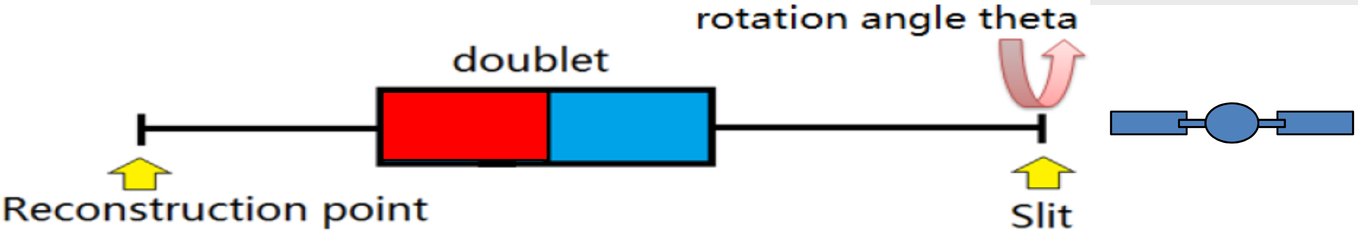


Measurement of the transverse four-dimensional beam rms-emittance of an intense uranium beam at 11.4 MeV/u, C. Xiao, L. Groening, P. Gerhard, M. Maier, S. Mickat, H. Vormann: **NIMA 2016, doi: 10.1016/j.nima.2016.02.090**

ROSE – the idea
instead of rotating the beam we could:



ROSE
measurement principle



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

All values are measured using Rose behind a magnetic doublet at the final position C_{final}. Knowing the transfer matrix they can be calculated back to the reconstruction point of the original not changing beam matrix $C_{initial}$. 100% transmission between initial and final Position and full slit-grid coverage is of course required for all magnet settings.

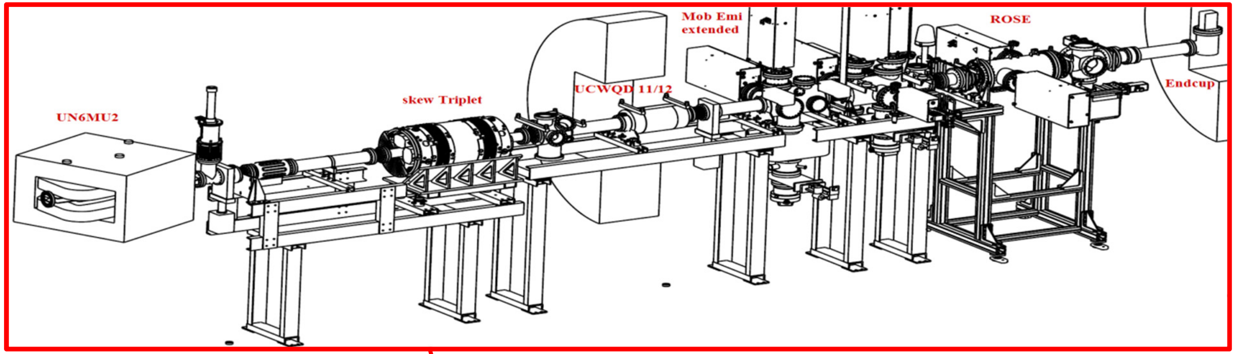
1. θ=90° magnet setting **a** delivers $\langle xx\rangle_f^a$, $\langle xx'\rangle_f^a$, $\langle x'x'\rangle_f^a$
2. θ=0° magnet setting **a** delivers $\langle yy\rangle_f^a$, $\langle yy'\rangle_f^a$, $\langle y'y'\rangle_f^a$
3. θ=45° magnet setting **a** delivers $\langle yy\rangle_\theta^a$, $\langle yy'\rangle_\theta^a$, $\langle y'y'\rangle_\theta^a$
4. θ=45° magnet setting **b** delivers $\langle xx\rangle_\theta^b$

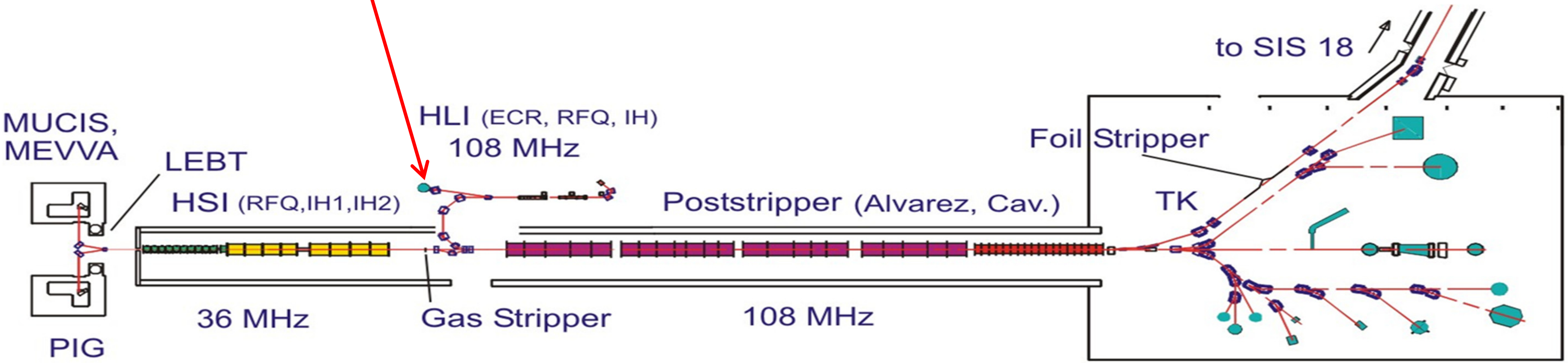
only 4 measurements and quite some matrix gymnastics needed to obtain the full beam matrix

- Deutsche Patentanmeldung Nr. 102015118017.0
- Rotating system for four-dimensional transverse rms-emittance measurements, C. Xiao, M. Maier, X. N. Du, P. Gerhard, L. Groening, S. Mickat, and H. Vormann, **Phys. Rev. Accel. Beams 19, 072802 (2016)**

ROSE
commissioning setup

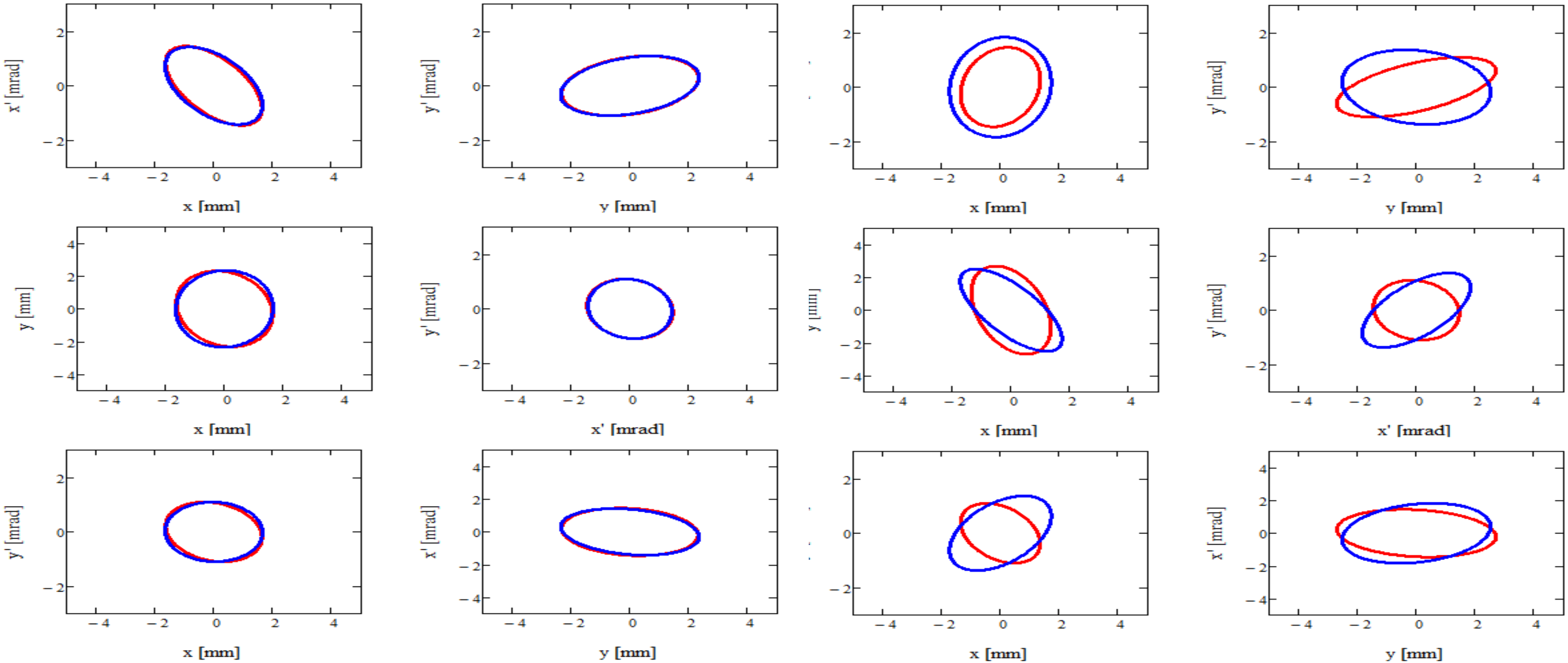
- measurements at exit of GSI's HLI
- 1.4 MeV/u of $^{40}Ar^{9+}$ and $^{83}Kr^{13+}$
- skew triplet to create x↔y correlations
- full transmission





ROSE
proof of principle

reconstruction point in front of skew | measured emittance at the slit



red skew off, **blue skew on**

ROSE
for a fully standalone 4D emittance scanner

Until here, the GSI control system has been used, yet for a mobile emittance scanner a new, accelerator control system independent electronics is needed only requiring 230V and a trigger signal in case of pulsed beam operation. Due to the changes in the electronics some minor hardware changes on the detector system ROSE namely the step motors, end switches had been necessary.

Electronics - ROBOMAT*

There is not yet a software to mastermind, perform and evaluate the 4D measurements. Such a software package combining all these features still needs to be developed. Its basic function is to guide the user through the complicated 4D measurement process. In later development stages it may also suggest coupling and decoupling schemes for given ion optic layouts.

Software - FOUROSE**

FOUR-ROSE, ROSOFT, ROSEAPP, ROSEWARE, PROROSE, ROSEGRAM
RUNROSE, ROSELYZER, ROSECONTROL, ROSESET

Actually the measurements are not more complicated then any set of emittance measurements, yet to obtain the 4 dimensional beam matrix a set of four linear independent equations has to be solved. The software shall provide the tools to prepare the magnet settings necessary to obtain these linear independent settings with 100% transmission and to evaluate and present the resulting 4 dimensional beam matrix to the user including error studies.

*gefördert durch: Bundesministerium für Wirtschaft und Energie. WIPANO
**Dieses Projekt (HA-Projekt-Nr.: 694_19-14) wird im Rahmen der Innovationsförderung Hessen aus Mitteln der LOEWE

Gefördert durch:
Bundesministerium für Wirtschaft und Energie
aufgrund eines Beschlusses des Deutschen Bundestages

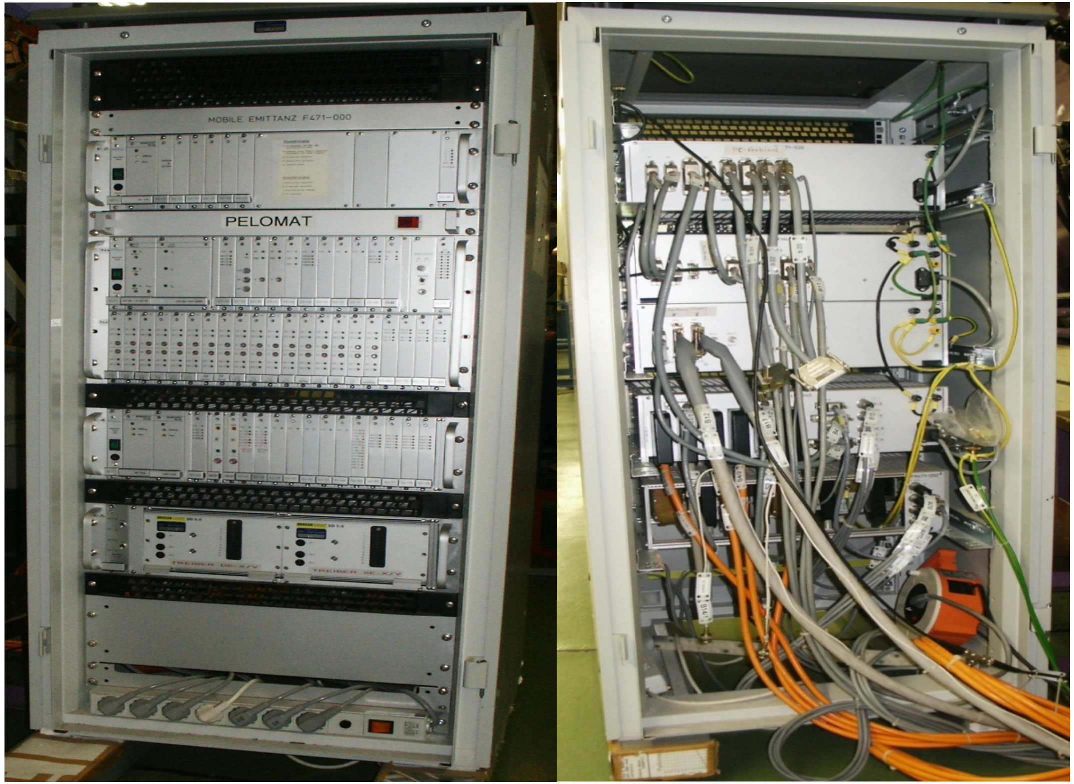
HESSEN
Hessisches Ministerium für Wissenschaft und Kunst

LOEWE
Exzellente Forschung für Hessens Zukunft

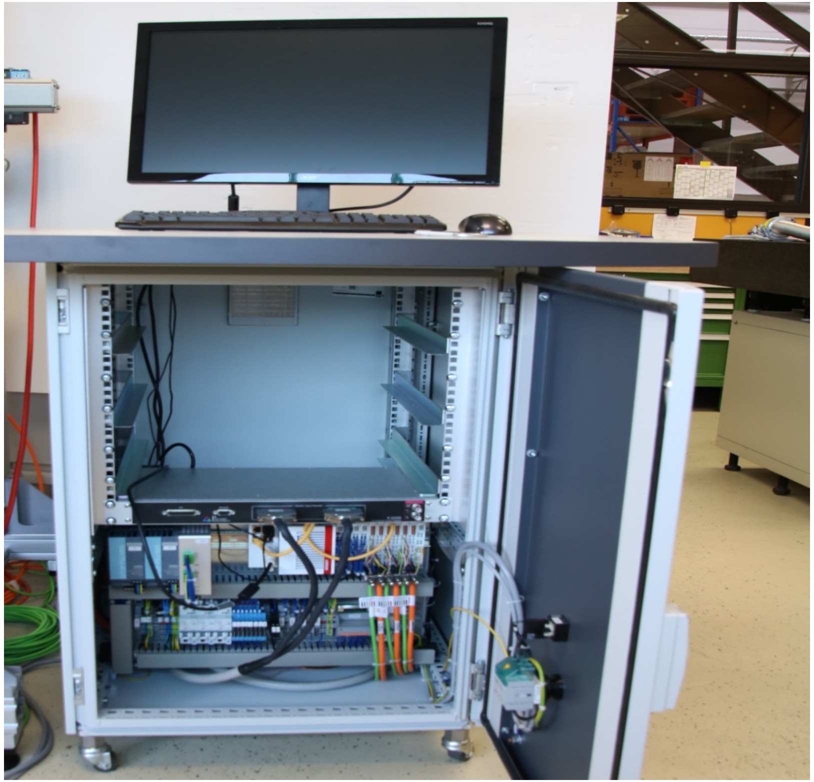
ROBOMAT
a standalone mobile emittance scanner

ROBOMAT: a modern version of our previous GSI electronics “Pelomat” from the mid 90’s using grid electronics of the 80’s

Pelomat 1990

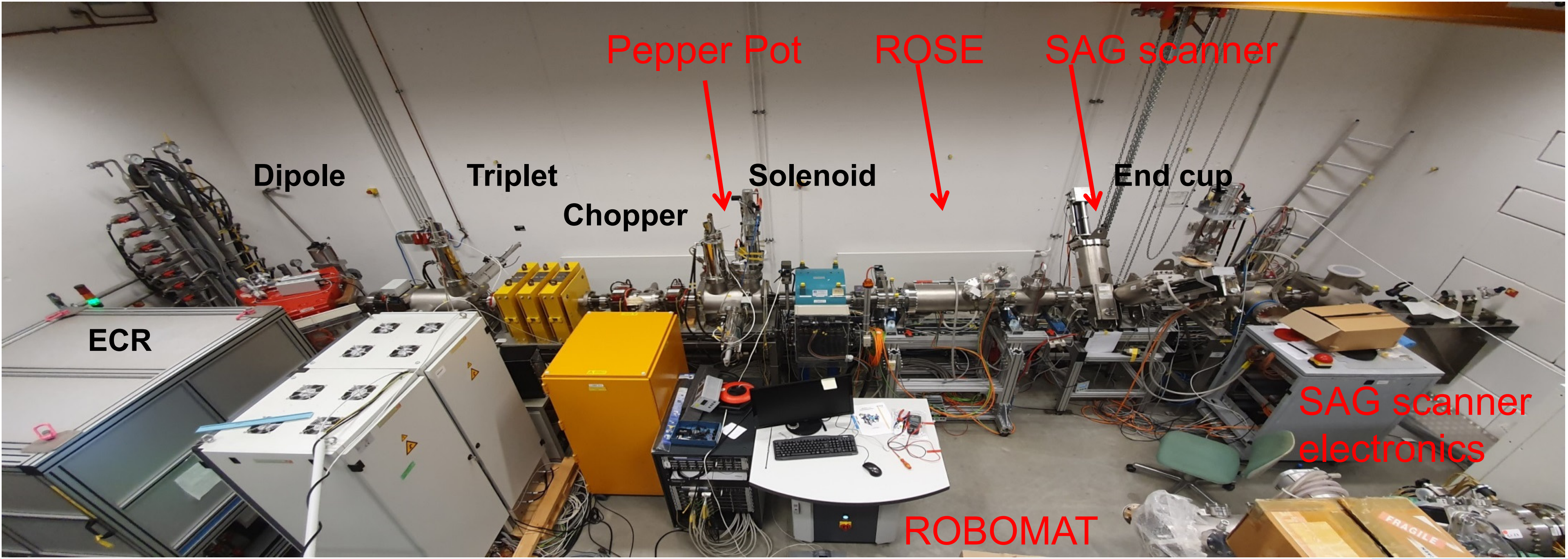


ROBOMAT 2019



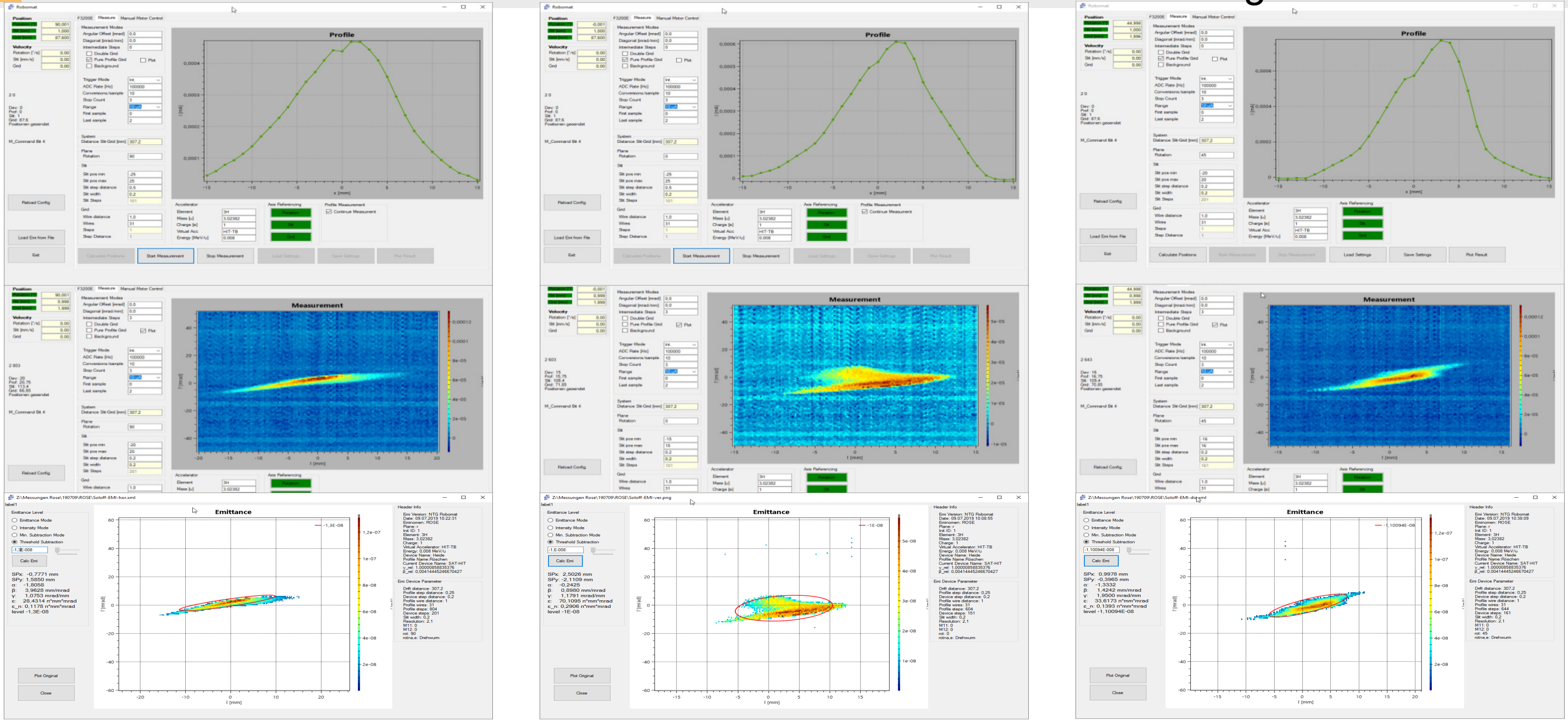
ROBOMAT
Site acceptance test

Has been successfully commissioned using H_3^+ at an ECR ion source and RFQ test bench of the Heidelberger ion therapy HIT facility in July 2019



ROBOMAT
data and evaluation

horizontal 90°	vertical 0°	diagonal 45°

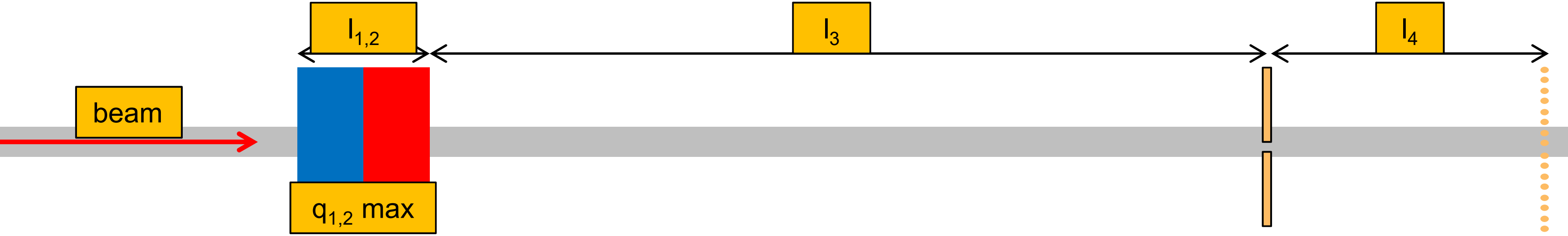


FOUROSE
software package funded by:

LOEWE
Exzellente Forschung für Hessens Zukunft

FAIR GSI

Guiding the user through ROSE 4D emittance measurements – started May 2019

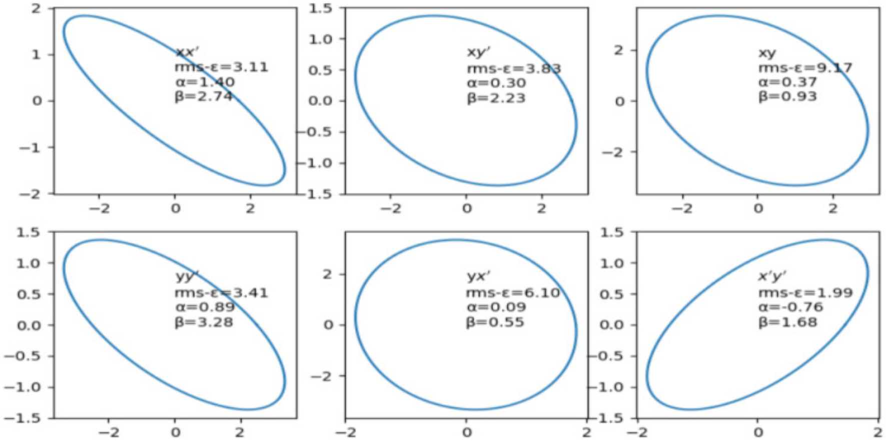


1. User entry of basic information e.g. beam line geometry and maximum field strength, beam parameters
2. User selection of measurement mode: profile grid, 2d-, **4d-emittance**
3. 2d emittance with quadrupoles off to determine optimum quadrupole settings for the 4d-emittance
4. 4d emittance using the above quadrupole settings
5. Numerical and graphical evaluation of the 4d-Emittance
6. ...

C:

8.5400	-4.3485	-3.4124	-1.1521
-4.3485	3.3496	-0.5442	1.5196
-3.4124	-0.5440	11.2004	-3.0488
-1.1520	1.5197	-3.0488	1.8700

eigen ε1: 2.4451 eigen ε2: 1.9345

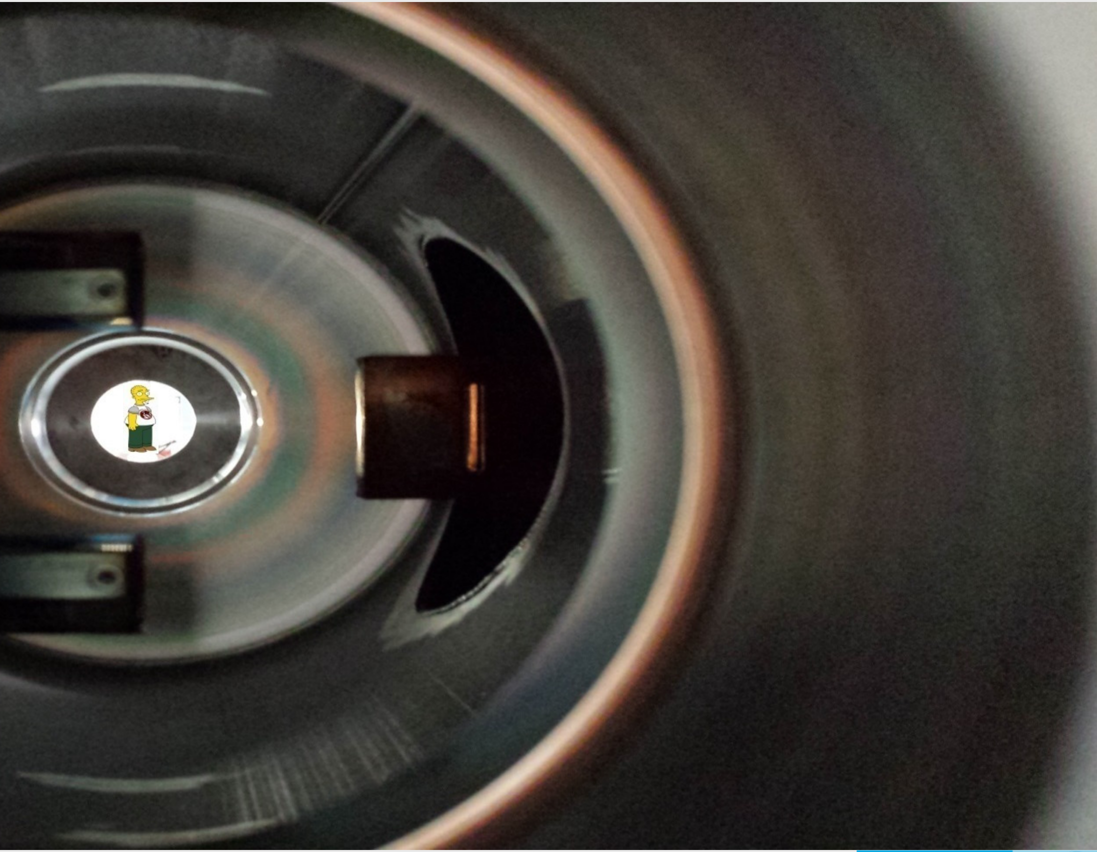


Conclusion

We have invented, build and successfully commissioned ROSE a 4D-emittance scanner for heavy ion beams independent of their kinetic energy, intensity and time structure.

Together with an industrial partner we have developed and commissioned the electronics ROBOMAT as a standalone, mobile emittance scanner.

The final part of this project has started this year and we expect to have the 4D application FOUROSE, as part of a configurable, mobile emittance scanner, ready in spring 2021.



Thank you very much for your attention

and my special gratitude to all the excellent people helping in this project

GSI Helmholtzzentrum für Schwerionenforschung GmbH

PSU post Stripper Upgrade
TTR technology transfer
BEA beam instrumentation
MDS mechanical design
MEW mechanical workshop
TRI transport and installation
VAC accelerator vacuum

UK HD HEIDELBERGER IONENSTRAHL-THERAPIEZENTRUM (HIT)

NTG

Gefördert durch:
Bundesministerium für Wirtschaft und Energie
aufgrund eines Beschlusses des Deutschen Bundestages

HESSEN
Hessisches Ministerium für Wissenschaft und Kunst

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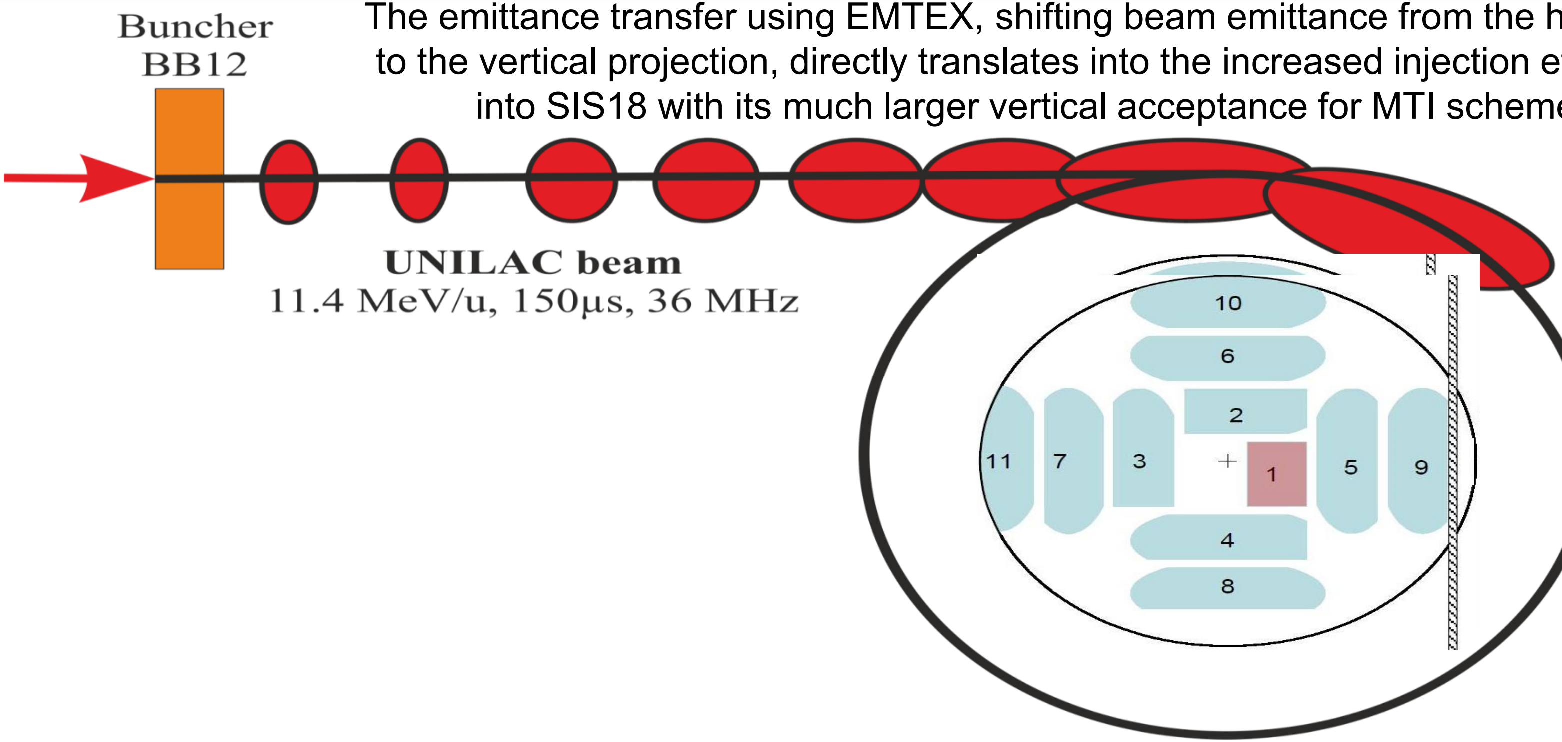
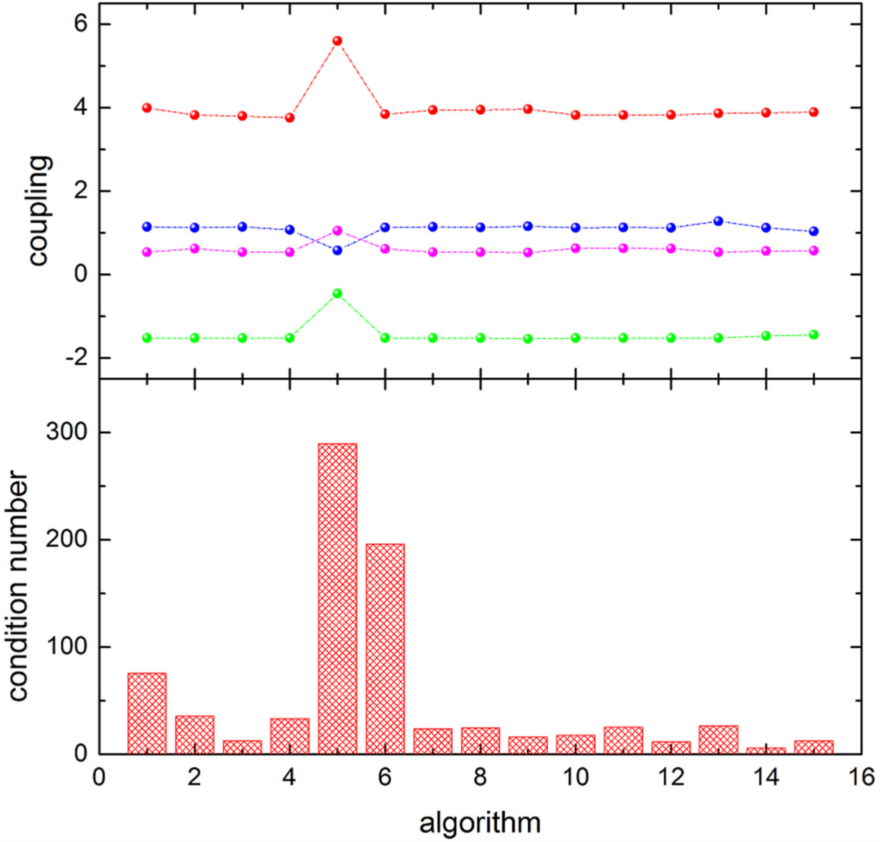
Motivation:
MTI into SIS18 using EMTEX

The emittance transfer using EMTEX, shifting beam emittance from the horizontal to the vertical projection, directly translates into the increased injection efficiency into SIS18 with its much larger vertical acceptance for MTI schemes



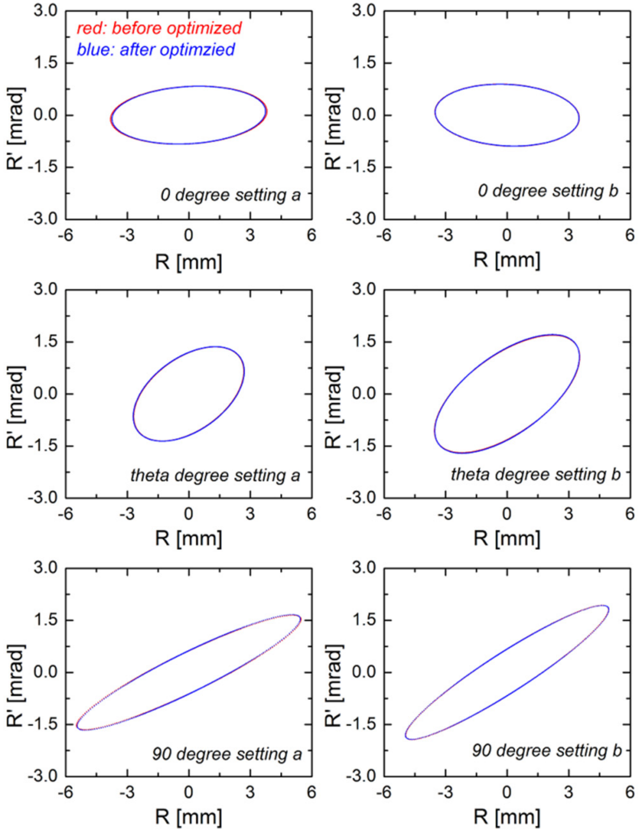
Software development



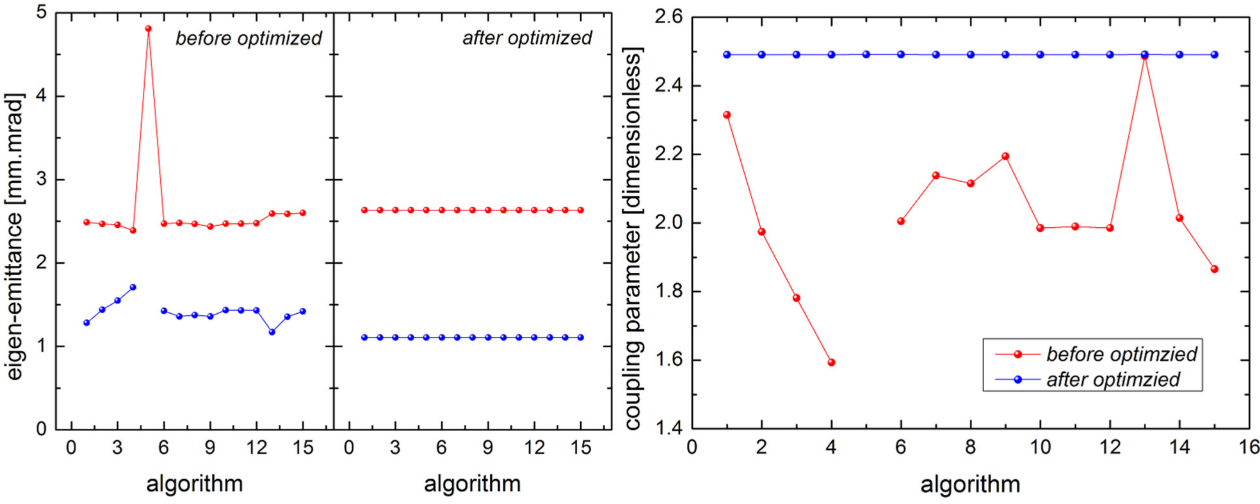
Besides developing a GUI and tool for the 4D beam emittance measurements there is also a lot of work considering the mathematic model enhancing the reliability and being more robust against measurement errors!

Small errors in the measured data lead to large deviations of the obtained Eigen emittances and thus of the coupling parameter for the available 15 algorithms of each 4 dimensional measurement as show in this figure.

Software development



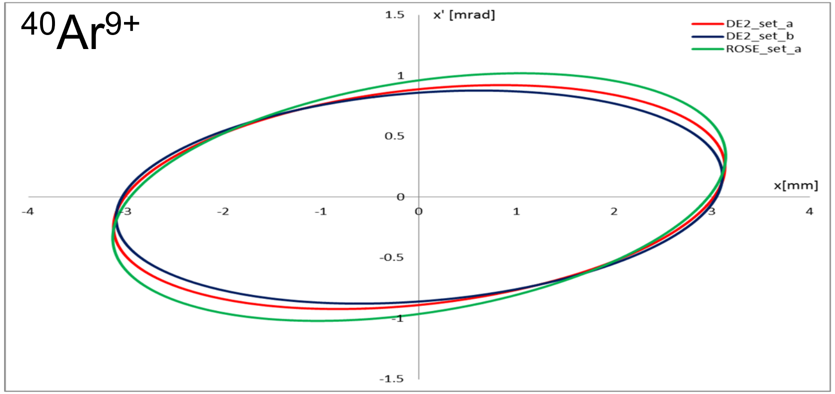
A new method has been developed to slightly vary the measured values within their error bars, to minimize the deviation in the resulting Eigen emittances. The variation of the measured value in this method is much smaller than the accuracy of the measurement, and thus not willingly faking the resulting data as can be seen in fig. 2. With this method it is possible to equalize all 15 algorithm results to fit a value of highest likelihood. (by courtesy of C.Xiao)

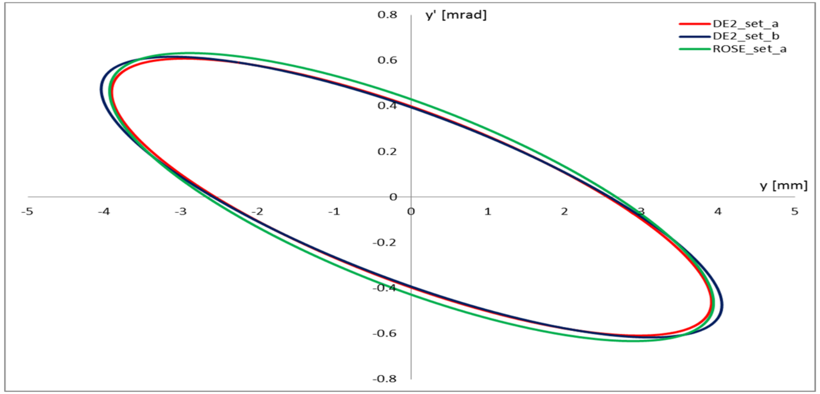


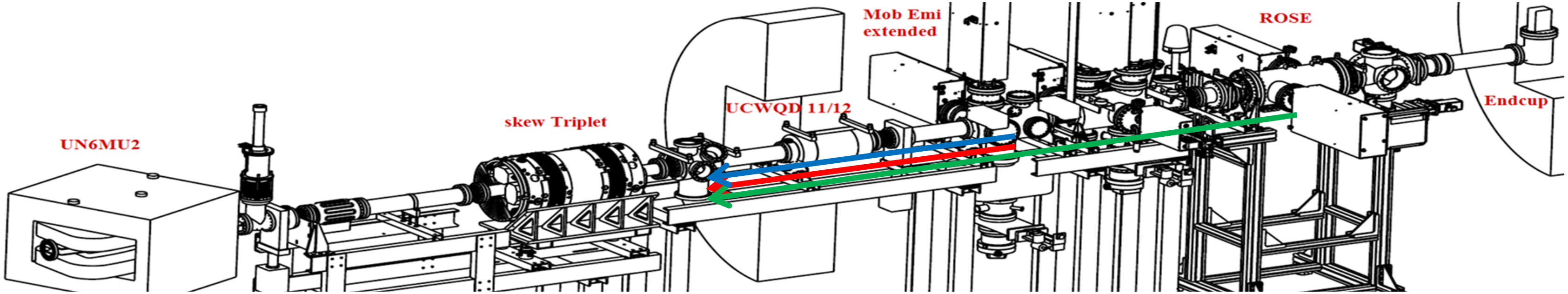
ROSE
benchmarking

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

$^{40}Ar^{9+}$



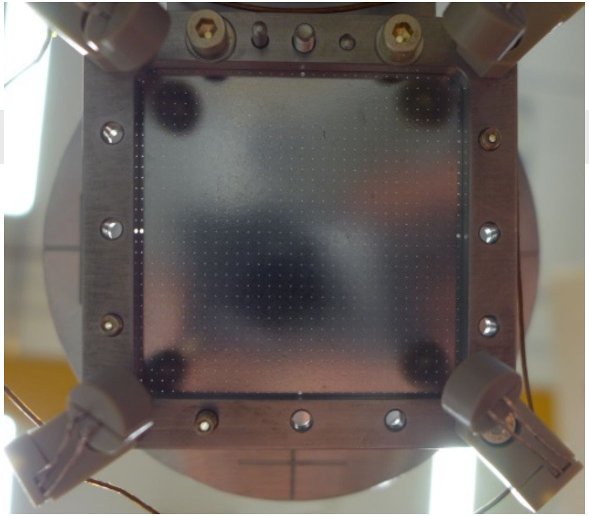




Pepperpot - HIT

Advantages:

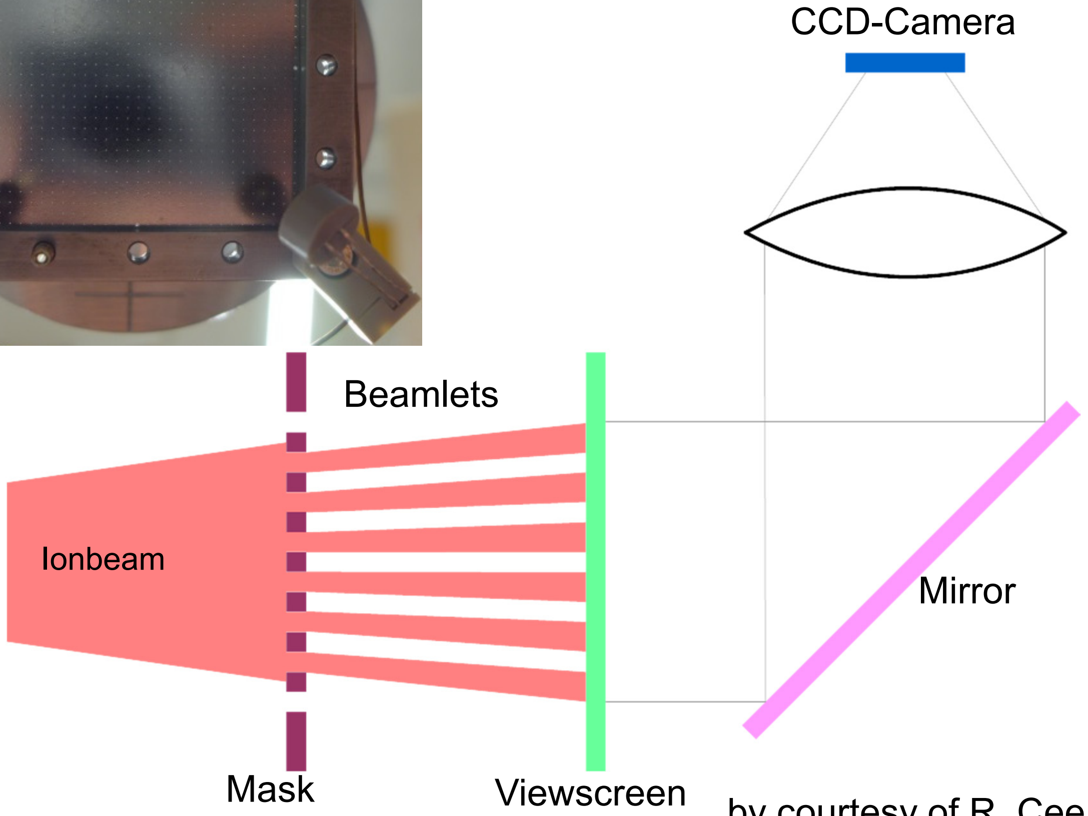
- fast, single pulse measurement
- Both planes simultaneously
- 4D coupling information not lost



Disadvantage:

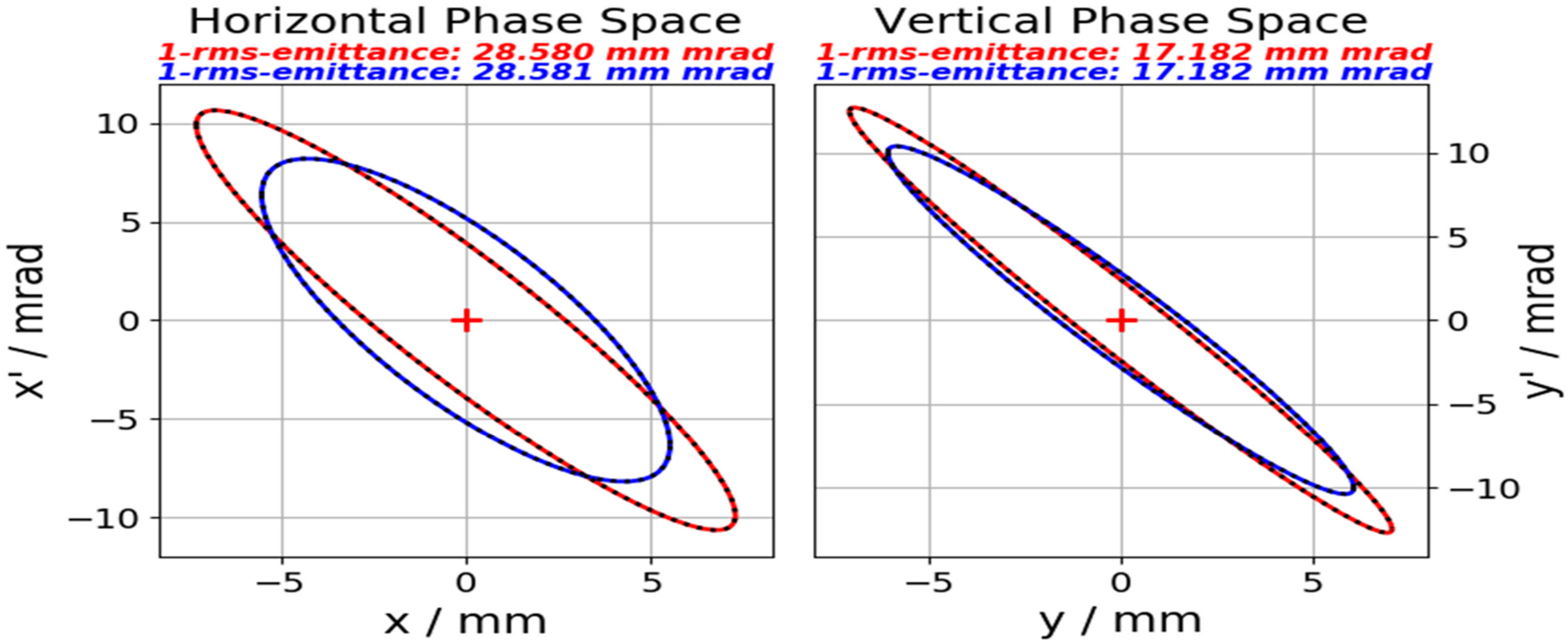
- limited angels as beamlets may not overlap
- Sensitive non linear response to beam power
- Strong energy limit due to mask stopping power
- Only a small fraction of the beam is measured, the rest is stopped in the mask
- Difficult data evaluation
- ....

To my knowledge not possible for ion beams above 150keV/u



by courtesy of R. Cee HIT

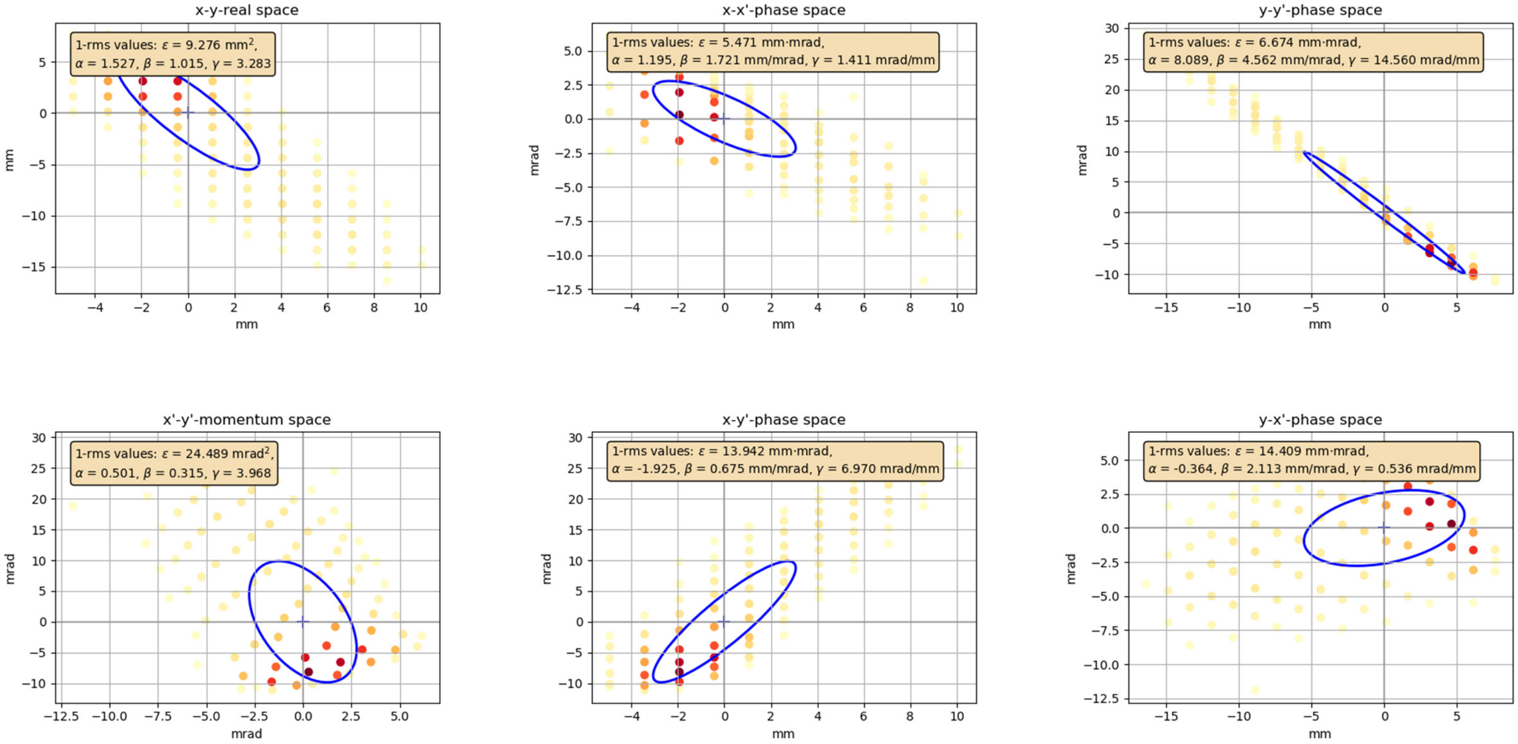
ROBOMAT
Benchmarking ROSE vs SAG scanner



— ROSE
— SAG

by courtesy of R. Cee HIT

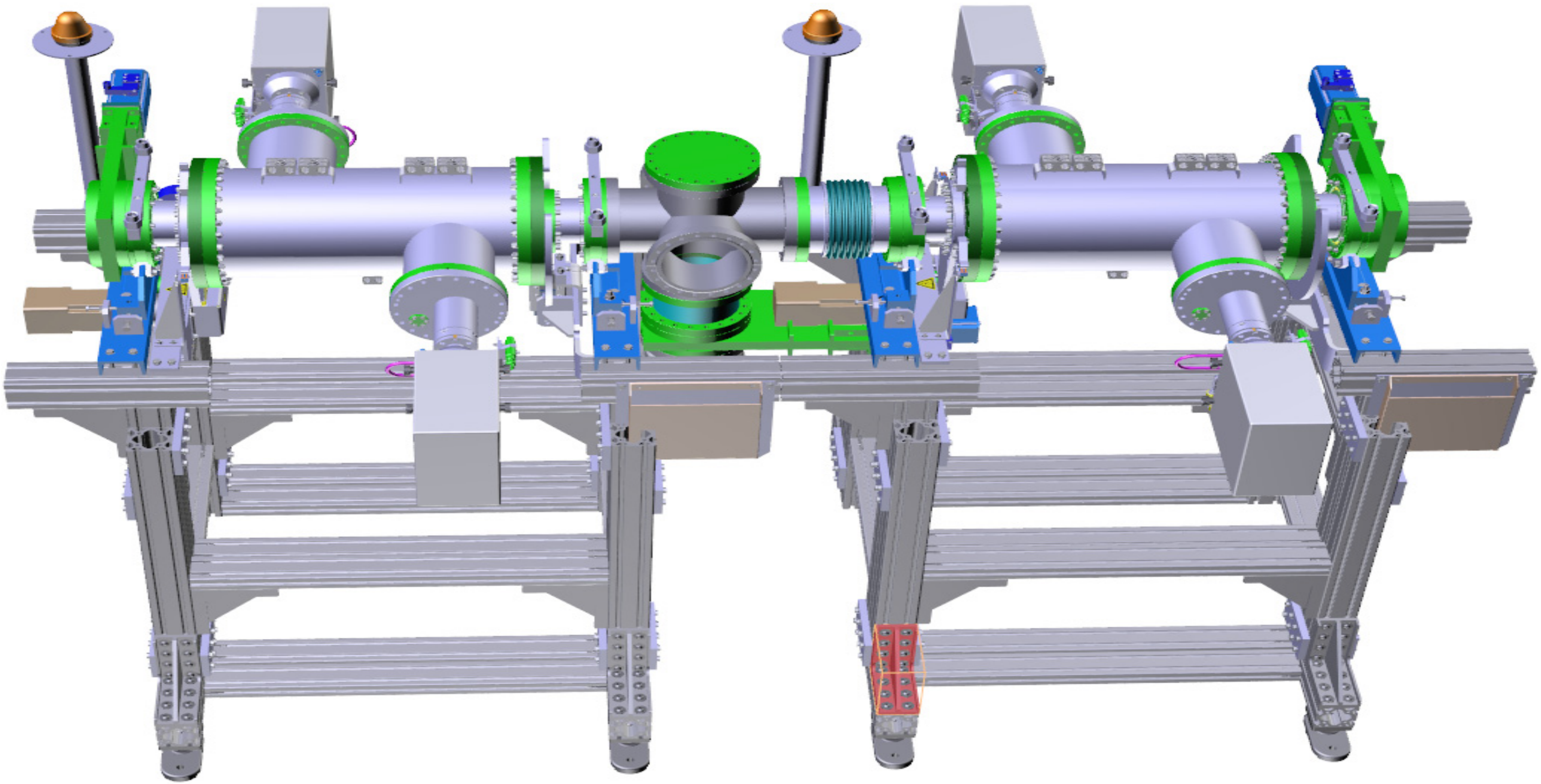
PP Measurements



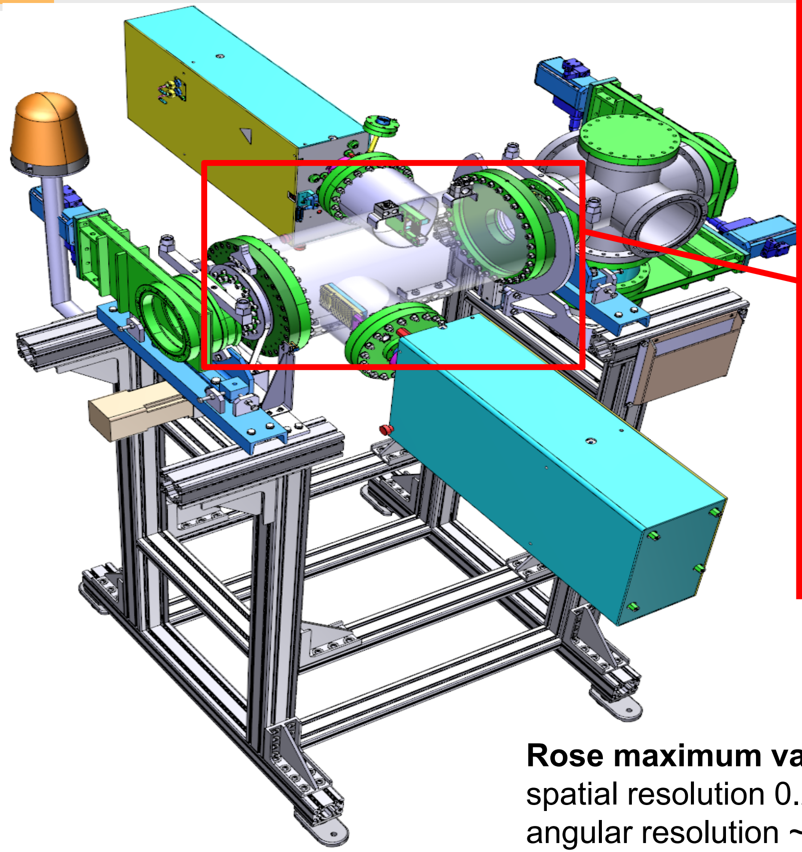
by courtesy of R. Cee HIT

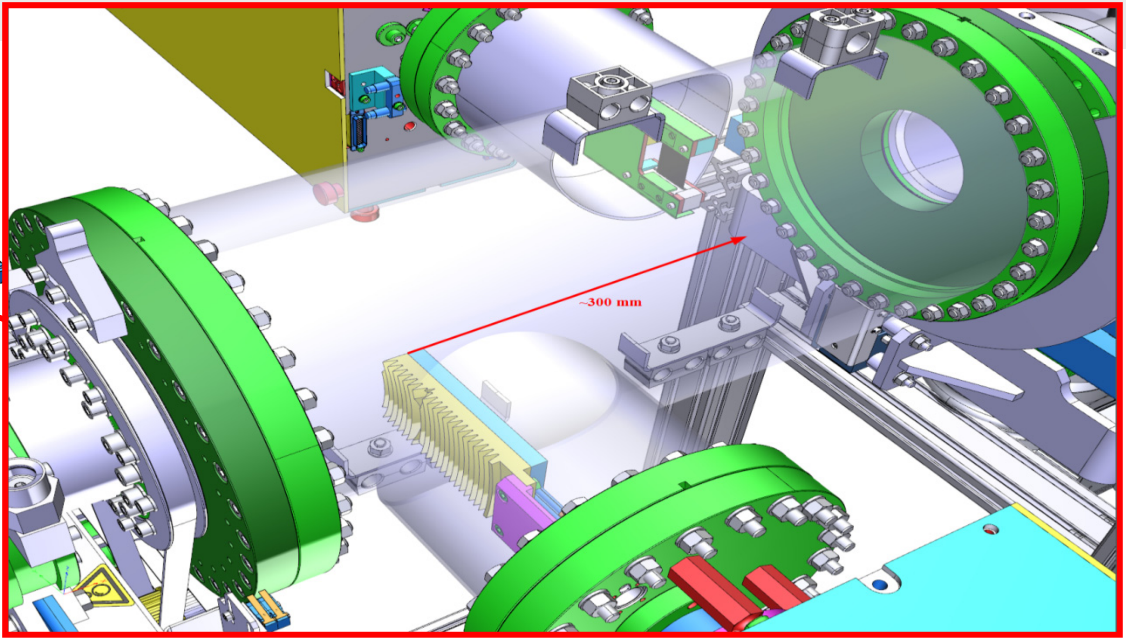
File: Strahl_3s_1.tiff

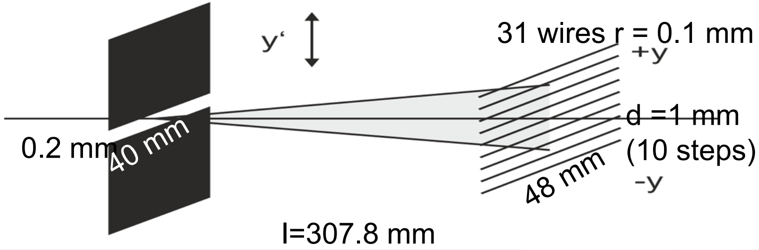
ROSE – Hardware modified for flexibility



ROSE – Hardware existing







Rose maximum values:
spatial resolution 0.2 mm
angular resolution ~3.25 (0.325) mrad
beam spot size (slit) < 40 mm

Condition number

- A minimum of four but more reliable six measurements are sufficient to measure the complete four-dimensional second-moments beam matrix.
  - 0° set a, *b can be calculated from set a*
  - 90° set a, *b can be calculated from set a*
  - 45° set a, b
- In order to match a reasonable beam size on the slit and gird and to reach the full transmission efficiency through the whole ROSE beam line, the strengths of Q1 and Q2 are varied separately. A routine based on MATHCAD was developed and optimized to obtain the minimum condition number. Since there are four unknown coupling parameters and six linear equations, in total fifteen algorithms are generated to calculate the coupling. $\binom{n}{k} = \frac{n!}{k!(n-k)!}$ $n = 6,$ $k = 4.$
- In this way the so-called safety island including all the optimized doublet settings can be found. The safety island and optimized doublet settings are shown here:

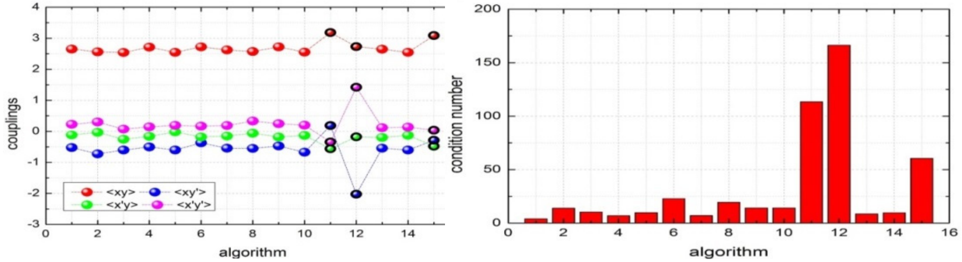
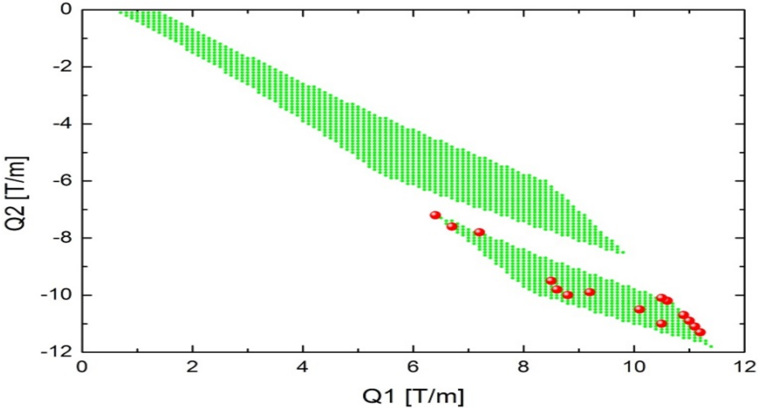
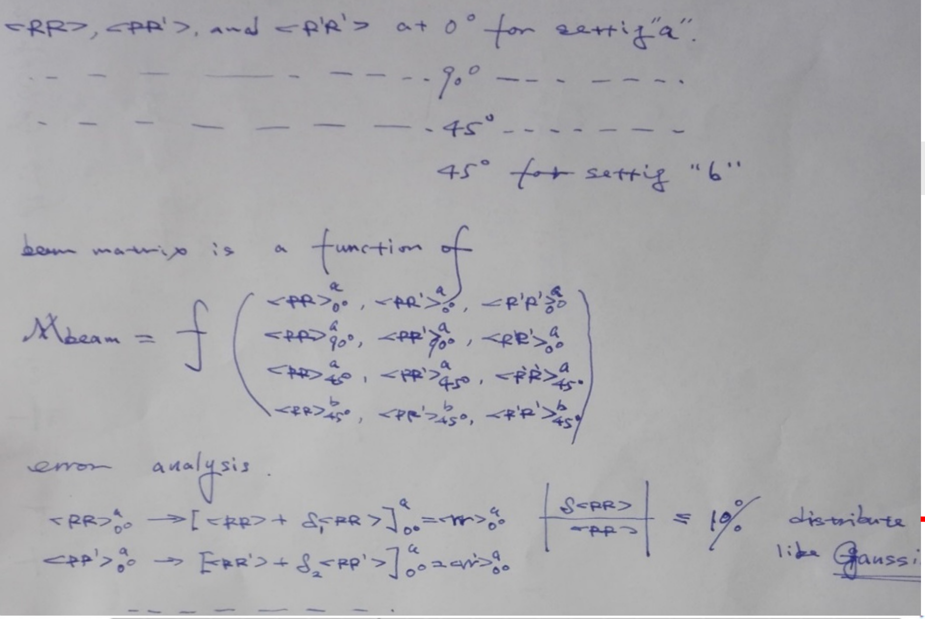


Figure 4-2 Left picture: Calculated beam coupled second-moments at the entrances of ROSE beam line. The dots inside a black circle are considered unreliable. Right picture: Condition numbers of the different algorithms using the same doublet setting.



*Rotating system for four-dimensional transverse rms-emittance measurements; C. Xiao, M. Maier, X.N. Du, P. Gerhard, L. Groening, S. Mickat, and H. Vormann; submitted to PRSTAB


$\langle RR\rangle$, $\langle PP'\rangle$, and $\langle P'R'\rangle$ at 0° for setting "a".
- - - - - - - - 90° - - - -
- - - - - - - - 45° - - - -
45° for setting "b"

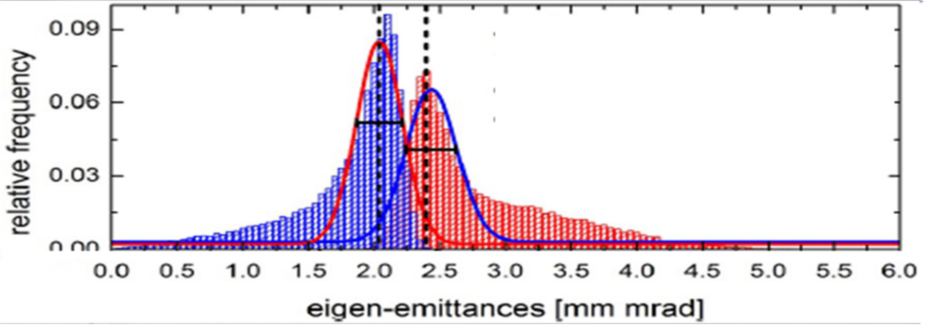
beam matrix is a function of

$$M_{beam} = f\begin{pmatrix} \langle PP\rangle^a_{0°}, & \langle PR'\rangle^a_{0°}, & \langle P'P'\rangle^a_{0°} \\ \langle PP\rangle^a_{90°}, & \langle PP'\rangle^a_{90°}, & \langle PR'\rangle^a_{0°} \\ \langle PP\rangle^a_{45°}, & \langle PP'\rangle^a_{45°}, & \langle P'R'\rangle^a_{45°} \\ \langle RR\rangle^b_{45°}, & \langle PP'\rangle^b_{45°}, & \langle P'R'\rangle^b_{45°} \end{pmatrix}$$

error analysis

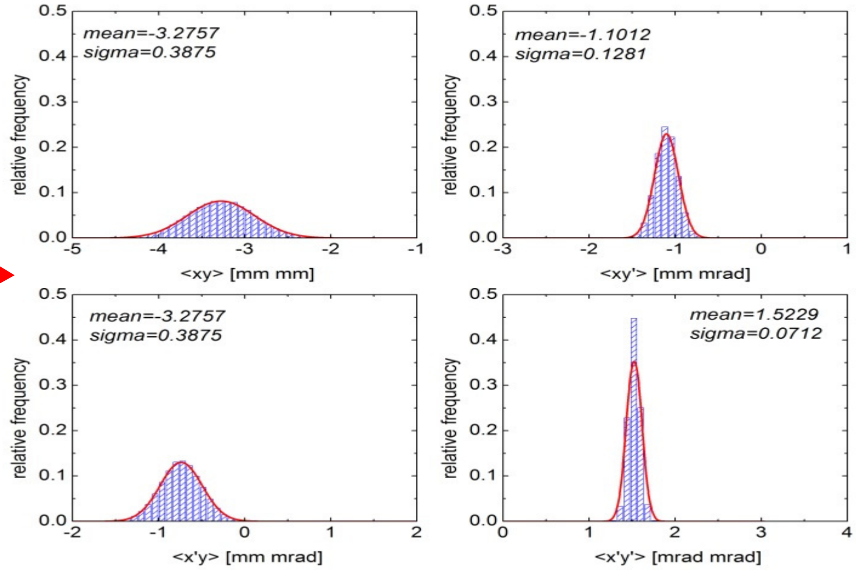
$\langle RR\rangle^a_{0°} \rightarrow [\langle RR\rangle + \delta_1\langle RR\rangle]^a_{0°} = \langle rr\rangle^a_{0°}$ $\quad \left|\frac{\delta\langle RR\rangle}{\langle RR\rangle}\right| \approx 1\%$ distribute like Gaussian

$\langle PP'\rangle^a_{0°} \rightarrow [\langle RR'\rangle + \delta_2\langle PP'\rangle]^a_{0°} = \langle rr'\rangle^a_{0°}$



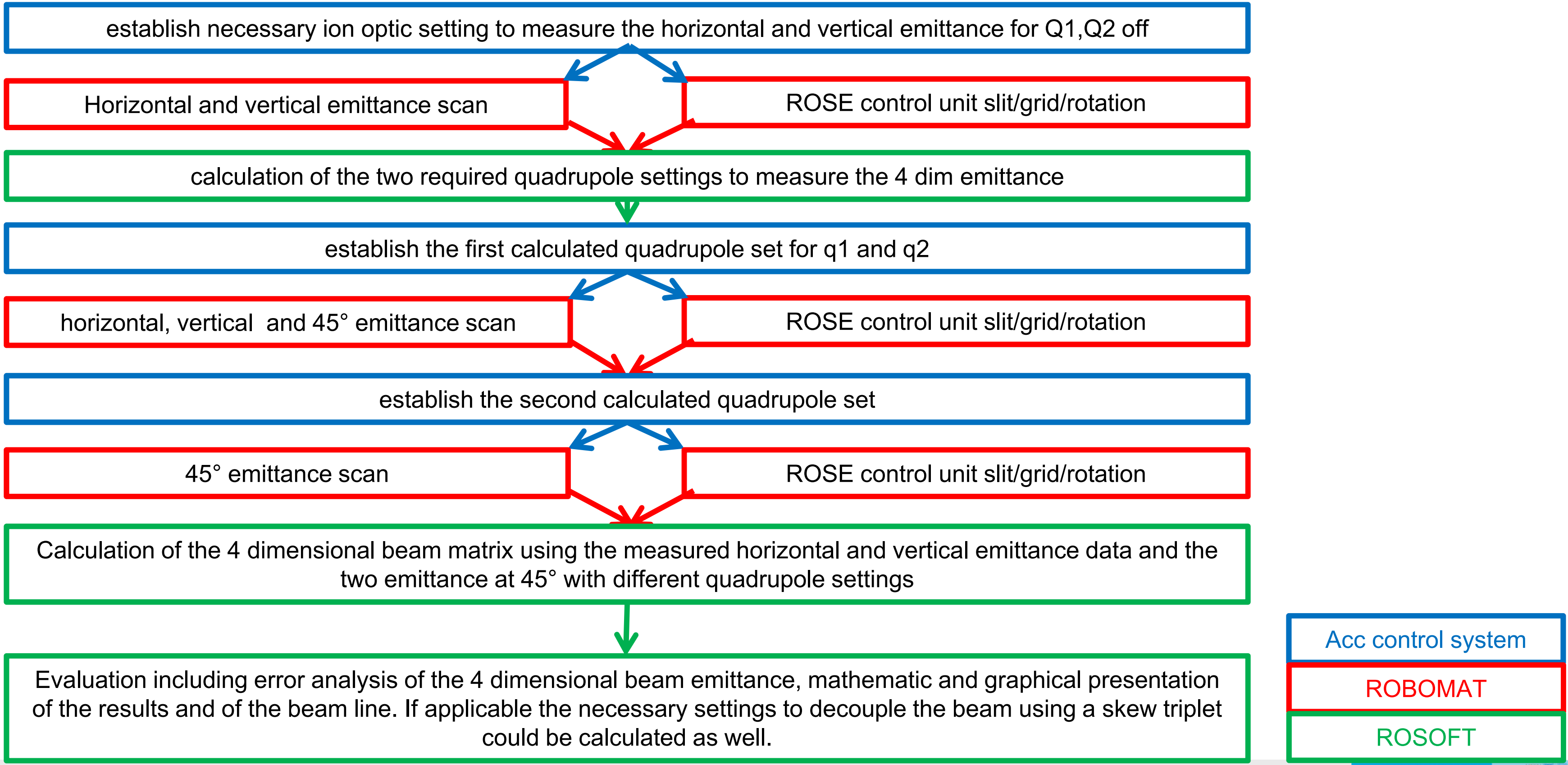
From the measured moments derived Eigen-emittances of the HLI 1.4 MeV/u $^{83}Kr^{13+}$ beam.

ROSE error studies



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

For a standalone 4D emittance scanner the ROSE software package is needed!



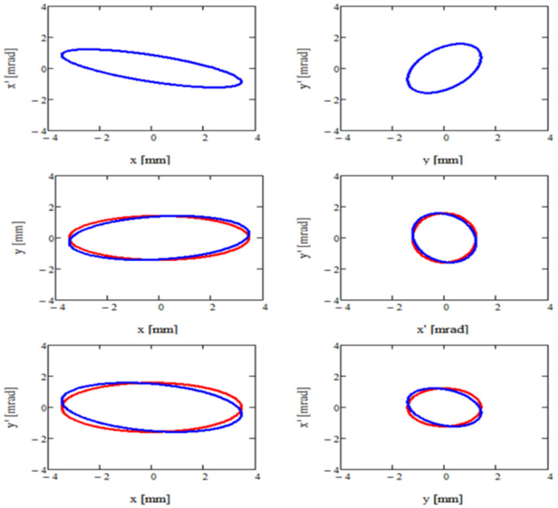
ROSE – motivation
beam envelopes along a solenoid channel

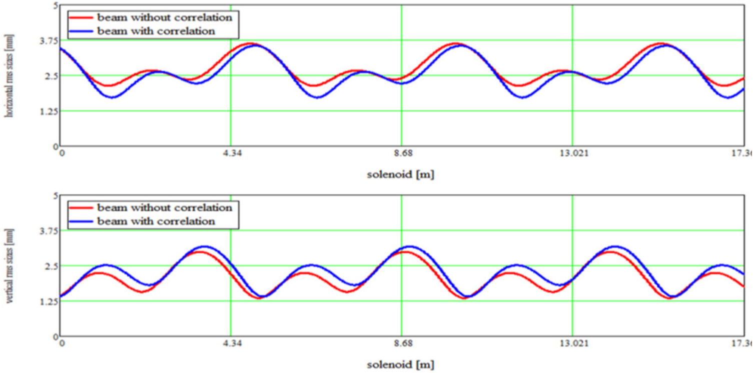
initial beam:

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

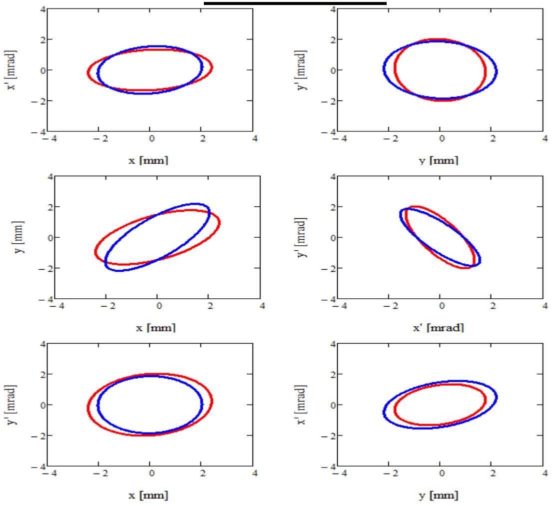
$$C_2=\begin{bmatrix} 12.00 & -3.00 & 1 & -1.5 \\ -3.00 & 1.50 & -0.5 & -0.35 \\ 1.00 & -0.50 & 2.00 & 1.00 \\ -1.50 & -0.35 & 1.00 & 2.50 \end{bmatrix} \text{ correlated}$$

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





final beam:



red and blue envelopes differ