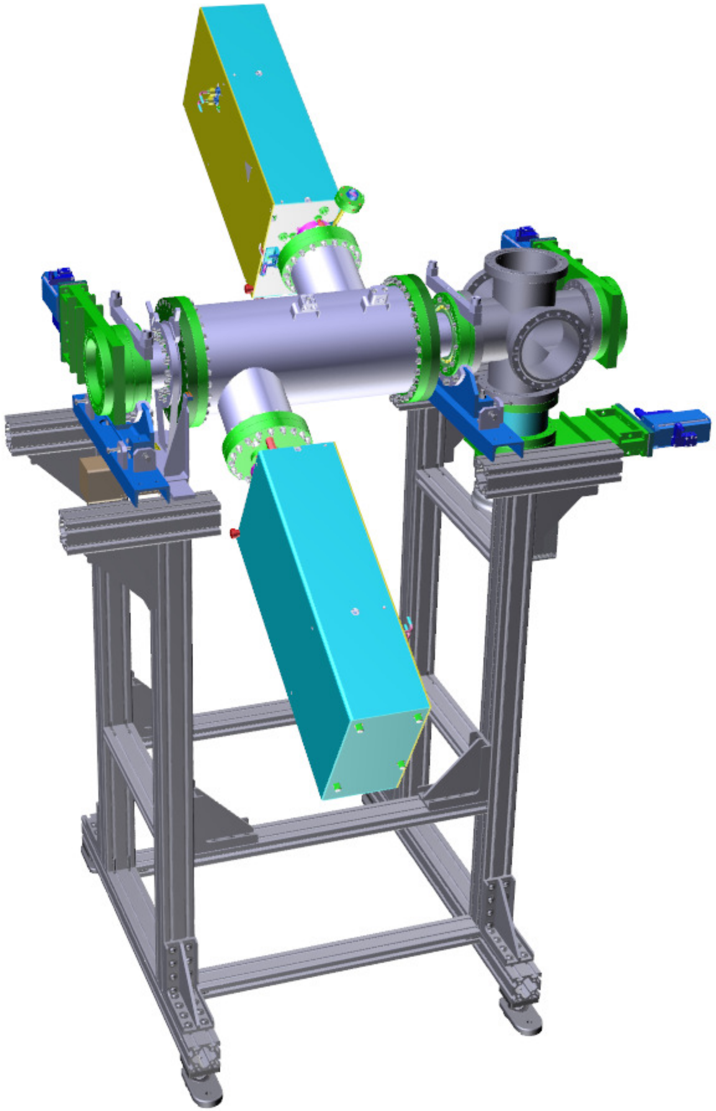
ROSE
Rotating **S**ystem for 4D-**E**mittance scans

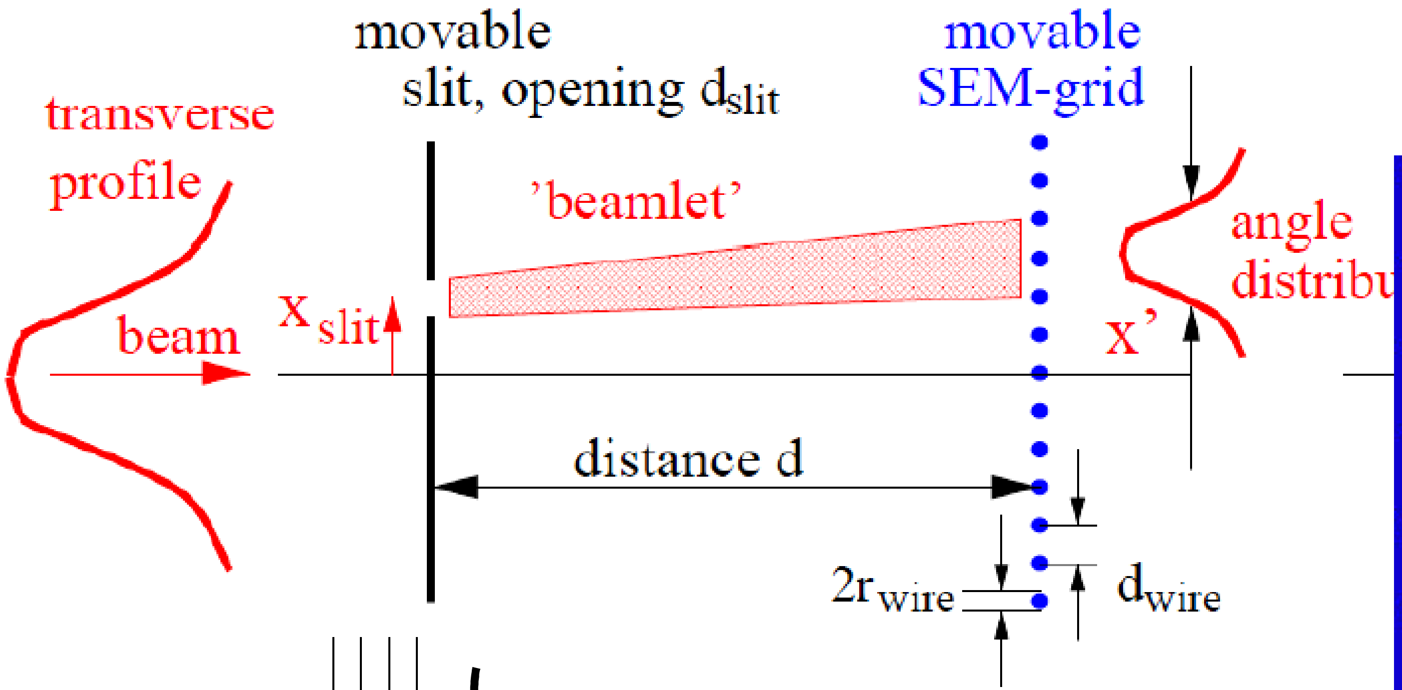


Content of this talk

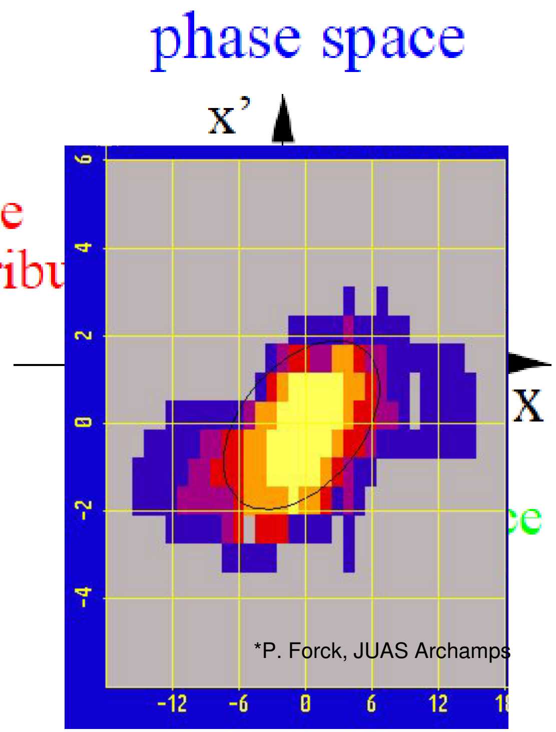
- **Theory**
  - Emittance measurement
  - The 4 dimensional beam matrix!
  - Examples
  - Applications
- **ROSE**
  - The idea
  - Technical solution
- **Commissioning results**
  - Experimental setup
  - benchmarking the slit-grid emittance scanner
  - Measurement of the beam matrix
  - Setup of Rose in front of SIS18 behind EMTEX
- **Outlook**
  - develop a turnkey 4d emittance scanner for the ion accelerator community.
  - ROBOMAT
  - ROSE Software

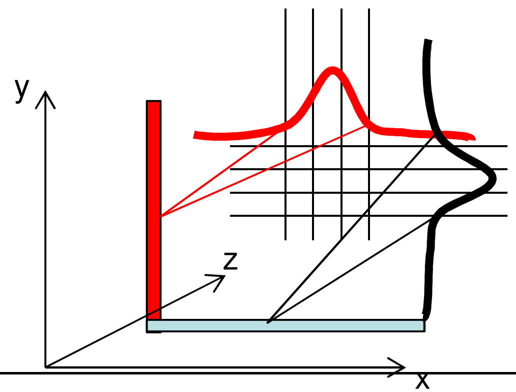
Theory
Slit-grid emittance measurement

Hardware



Analysis





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

Theory
The 4 dimensional beam matrix C

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

σ_x

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

σ_y

with ε_x=SQRT(det σ_x)

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

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

in here α, β, γ are the so called twiss parameters and ε_x the horizontal rms emittance

> The four-dimensional rms emittance ε_{4d} is the square root of the determinant of C, and the projected beam rms emittances ε_x and ε_y are the square roots of the determinants of the on-diagonal sub-matrices

Theory
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.

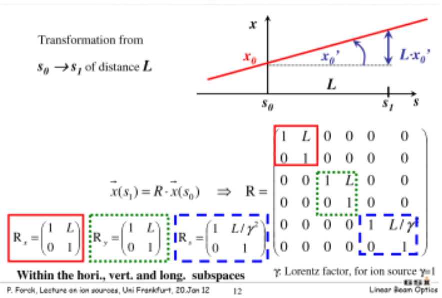
or in simple words: uncoupled beams are an idealization to simplify the beam dynamics and are a best case scenario. If the beam is correlated the projected emittances are larger than necessary and could be decreased!

Theory

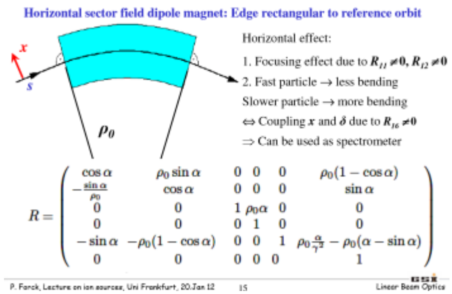
Why do we need to know?

Linear not coupling elements | **Linear coupling element**

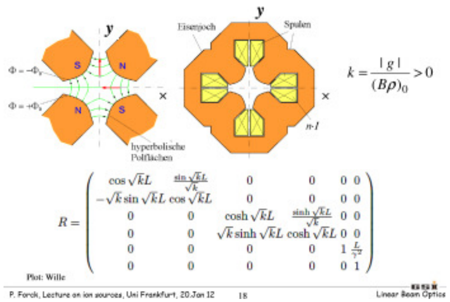
drift



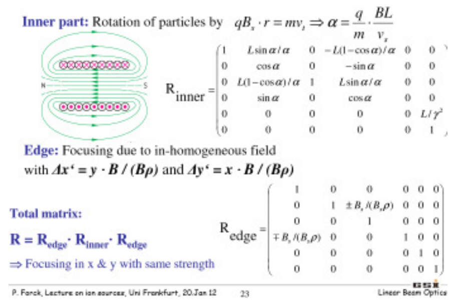
dipole



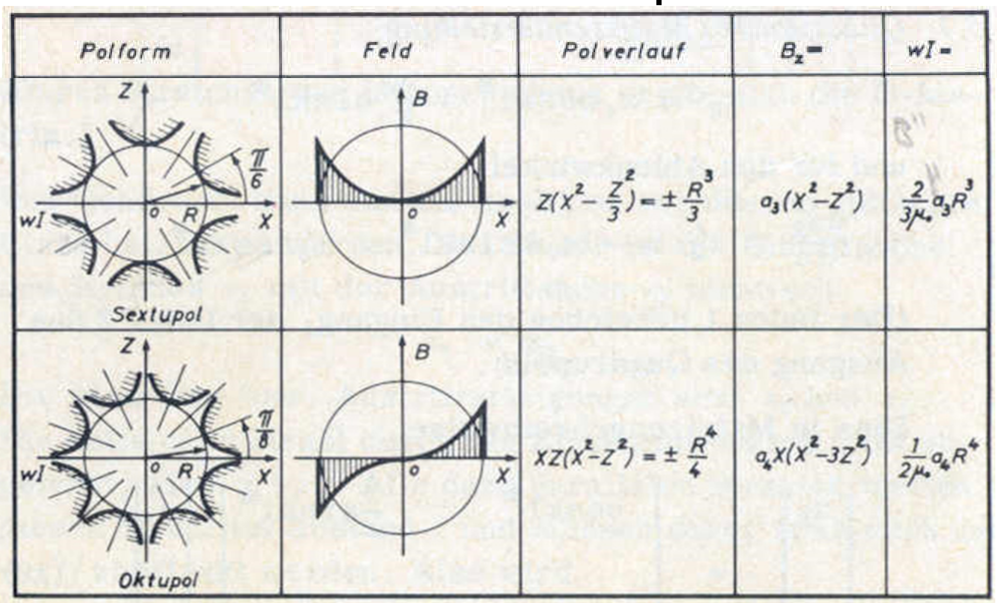
quadrupole



solenoid



Multipoles are non linear coupling elements



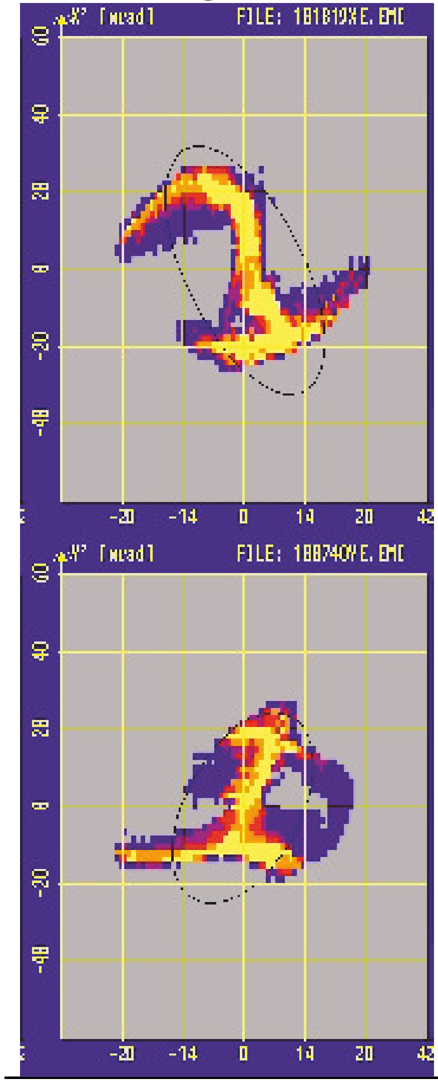
frequently used in:

- ion sources (solenoids, hexapoles)
- matching sections (solenoids, octupoles)
- Synchrotrons (hexapoles)
- ...
- beam loss may couple the planes as well

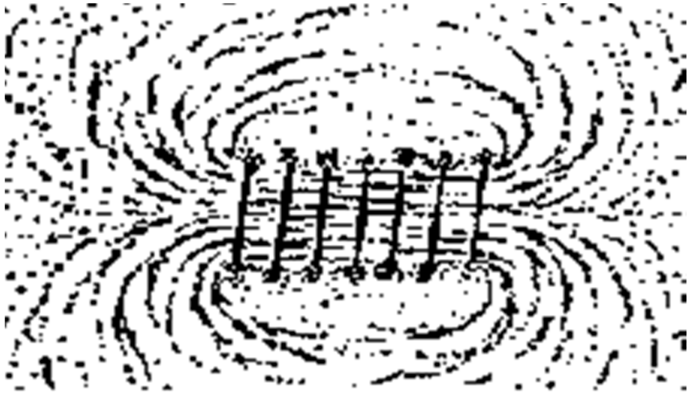
Example:

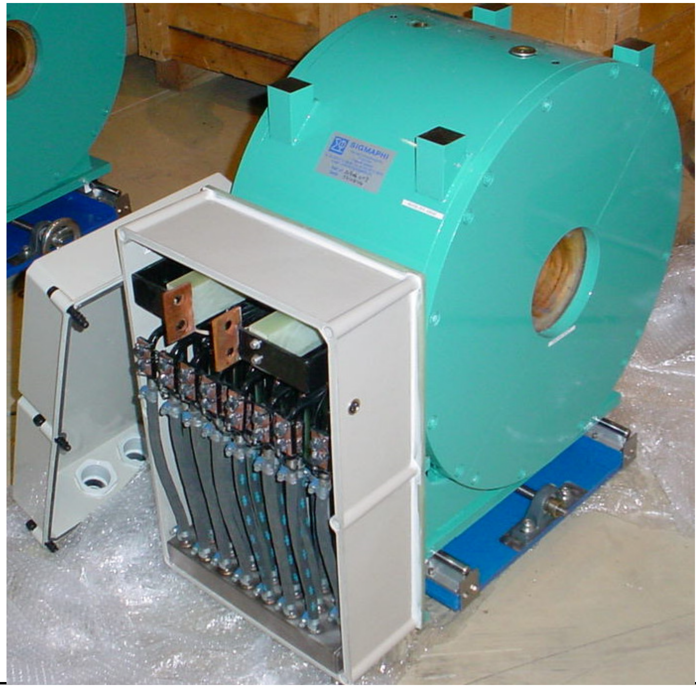
matching an ECR beam through a Solenoid into a RFQ
HIT, CNAO, GSI HLI, ...

ECR



Solenoid





Result

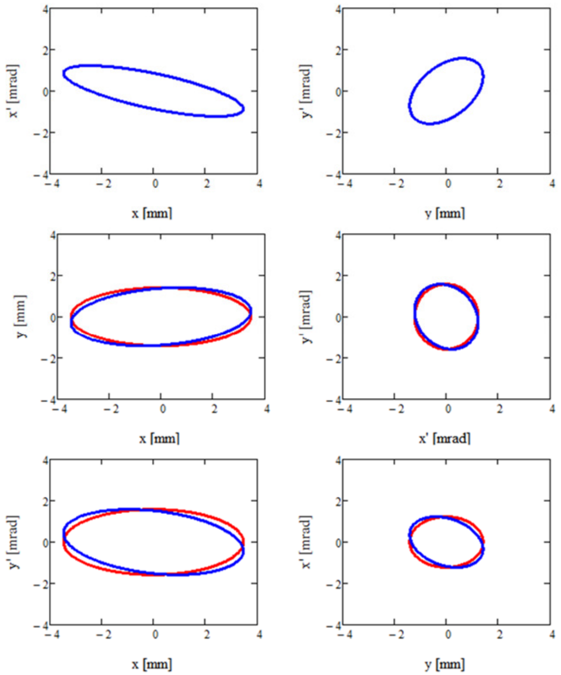
Theory

The solenoid in more detail

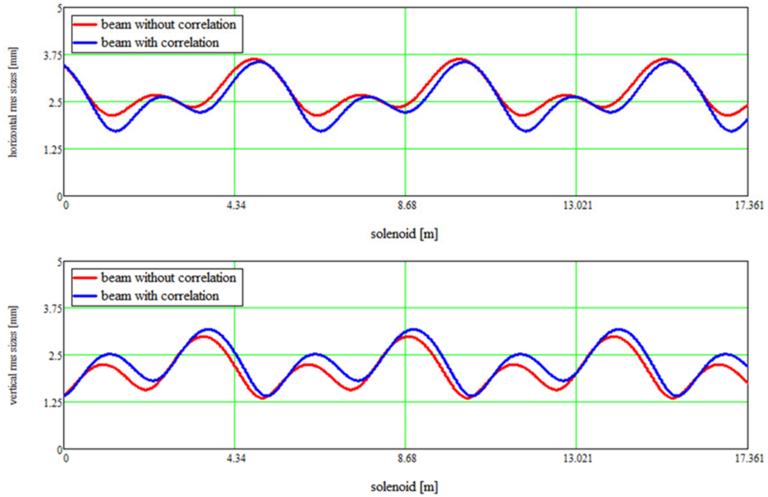
$$C1=\begin{bmatrix} 12.00 & -3.00 & 0.00 & 0.00 \\ -3.00 & 1.50 & 0.00 & 0.00 \\ 0.00 & 0.00 & 2.00 & 1.00 \\ 0.00 & 0.00 & 1.00 & 2.50 \end{bmatrix}$$ not coupled

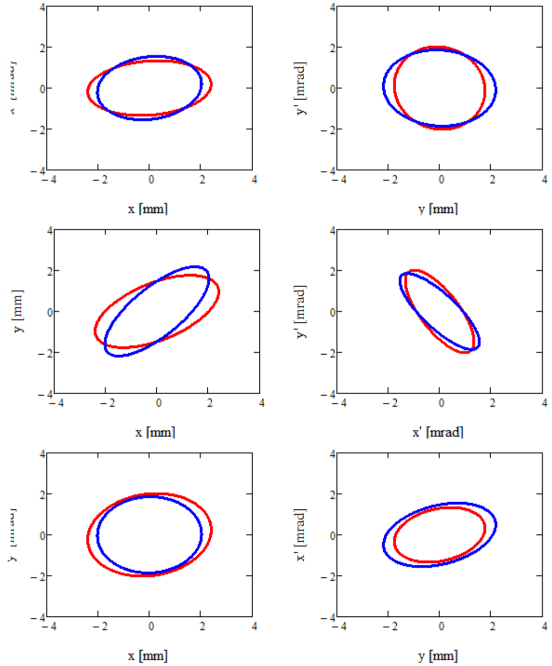
$$C2=\begin{bmatrix} 12.00 & -3.00 & 1 & -1.5 \\ -3.00 & 1.50 & -0.5 & -0.35 \\ 1.00 & -0.50 & 2.00 & 1.00 \\ -1.50 & -0.35 & 1.00 & 2.50 \end{bmatrix}$$ coupled

- **Correlations increase the projected rms-emittances in this case up to 10%.**
- **Removing correlations reduces the effective emittances without beam loss.**
- **In order to remove unknown correlations, they must be quantified by measurements.**



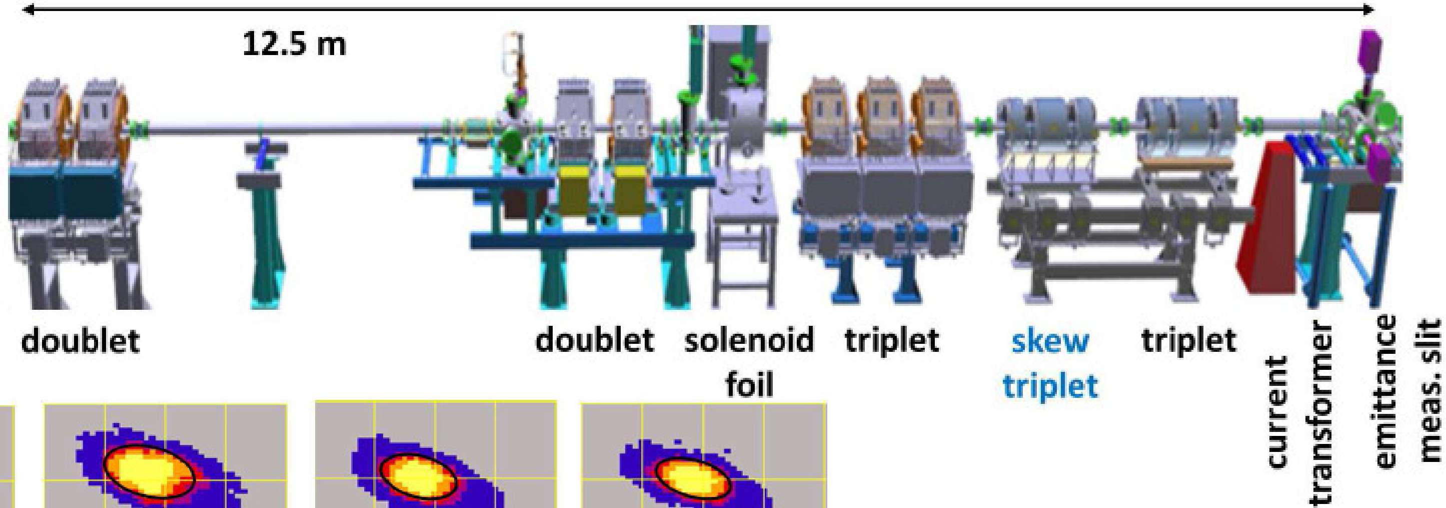
U28+; 11.4 MeV/u; Bz=5 T





Application using coupling of planes

EMTEX: flat beam creation using $^{14}N^{3+}$ at 11.4 MeV/u



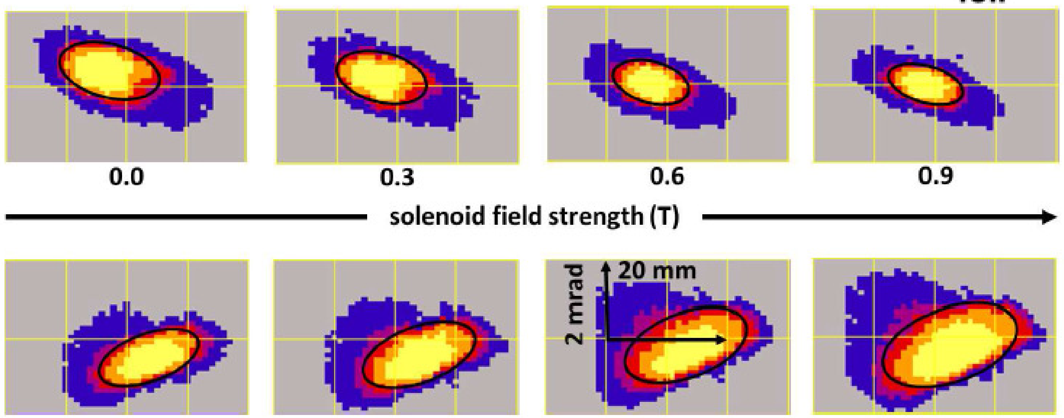
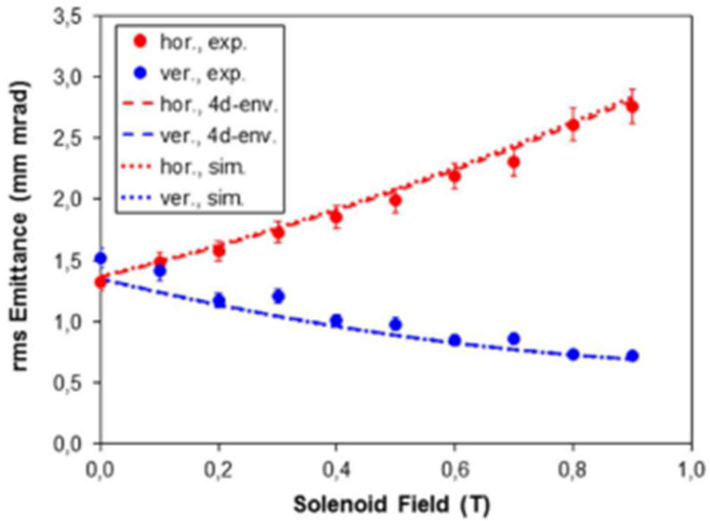
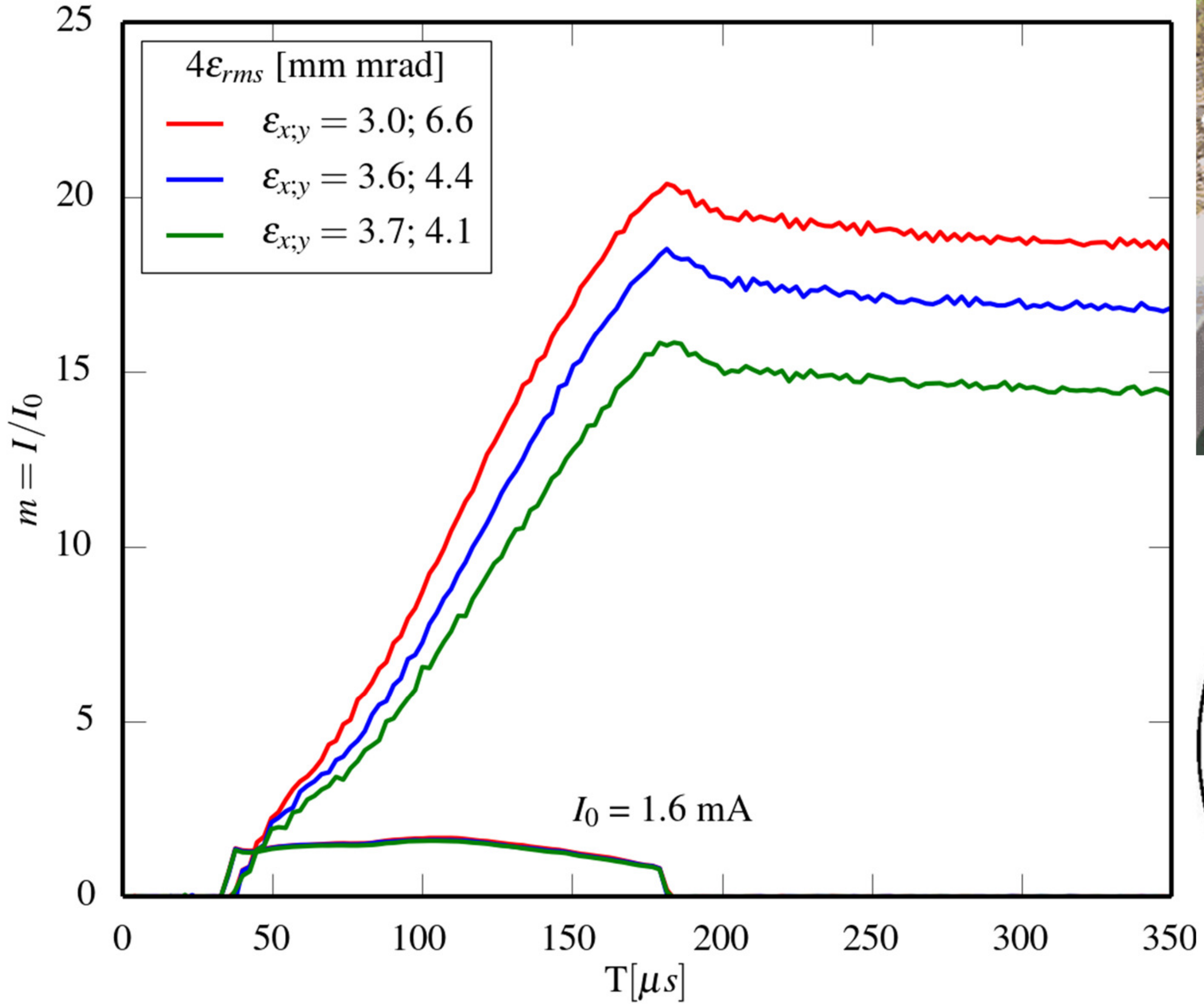


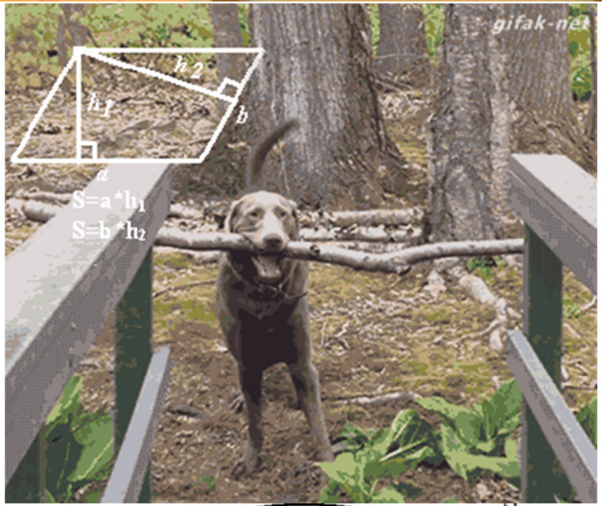
FIG. 4. (color online) Vertical (upper) and horizontal (lower) phase space distributions measured at the exit of the EMTEX beam line as functions of the solenoid field strength. All other settings were kept constant. Black ellipses indicate the 4×rms ellipses.

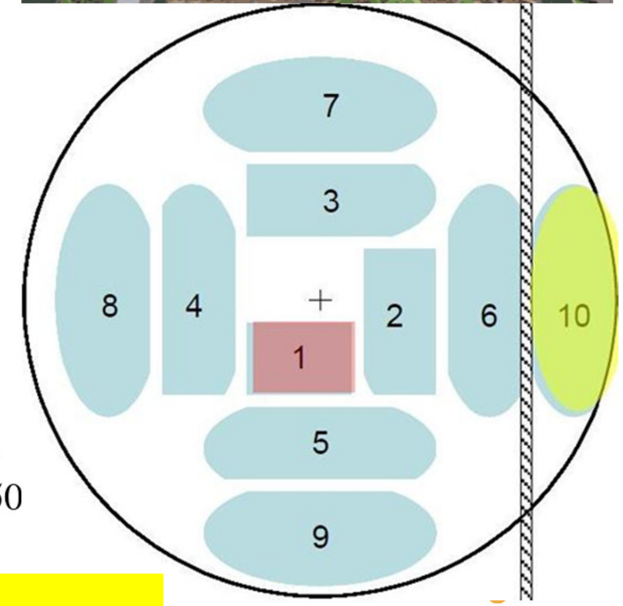


L. Groening, M. Maier, C. Xiao, L. Dahl, P. Gerhard, O.K. Kester, S. Mickat, H. Vormann, and M. Vossberg, Physical Review Letter, 113, (2014) 264802.

Application
MTI into SIS18 using EMTEX







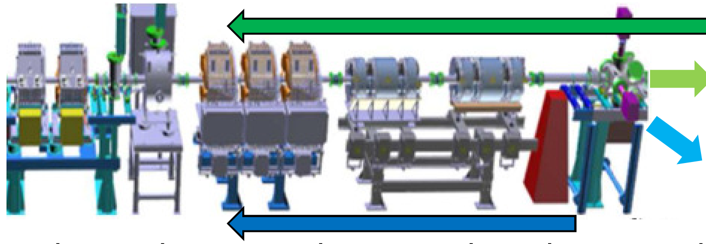
S. Appel et al., Injection optimization through generation of flat ion beams, NIMA Volume 866, 2017, Pages 36-39

Application

First measurement of the transverse 4d beam matrix

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 using 6 different skew quadrupole settings **assuming an uncorrelated beam** at the entrance of EMTEX results in the second-moment beam matrix**:**

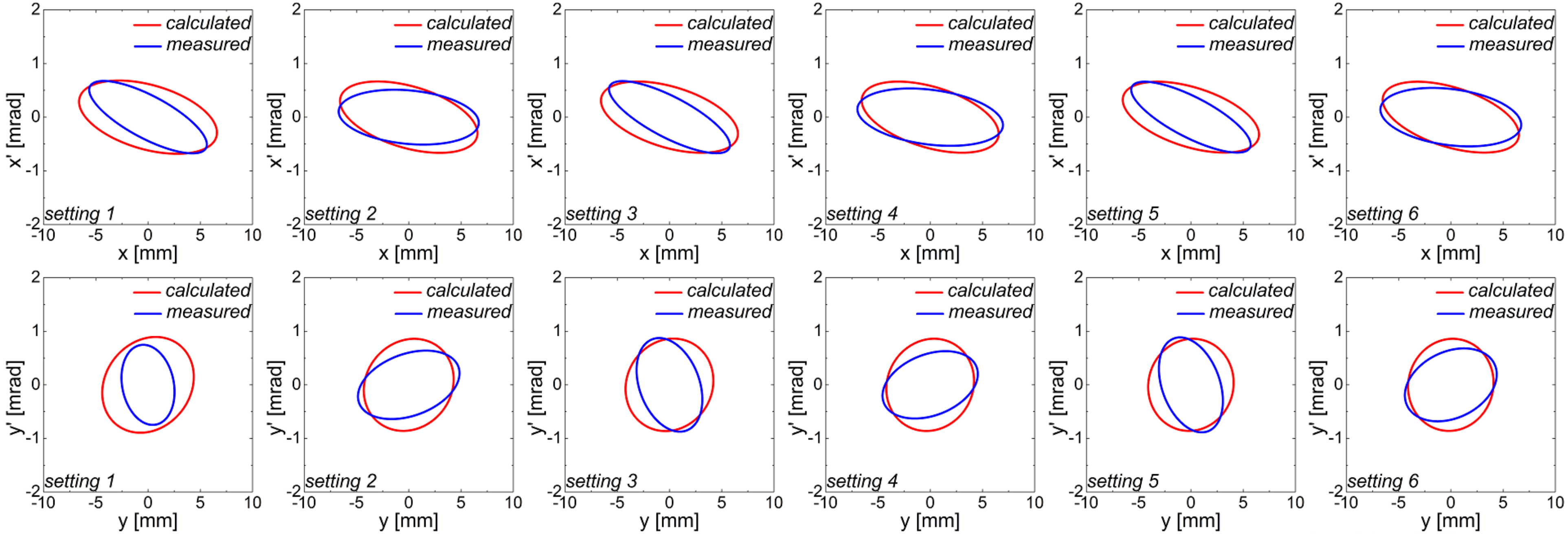
$$C_0 = \begin{pmatrix} 12.79 & 1.89 & 0 & 0 \\ 1.89 & 0.62 & 0 & 0 \\ 0 & 0 & 32.18 & 3.49 \\ 0 & 0 & 3.49 & 0.46 \end{pmatrix}$$



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

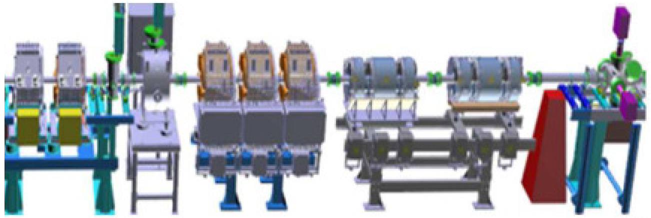
Repeating the measurements for turned on skews and comparing them to the simulations, using the above uncorrelated matrix, does not fit sufficiently well! Thus it is concluded the initial beam inhabits correlations.



Application
First measurement of the transverse 4d beam matrix

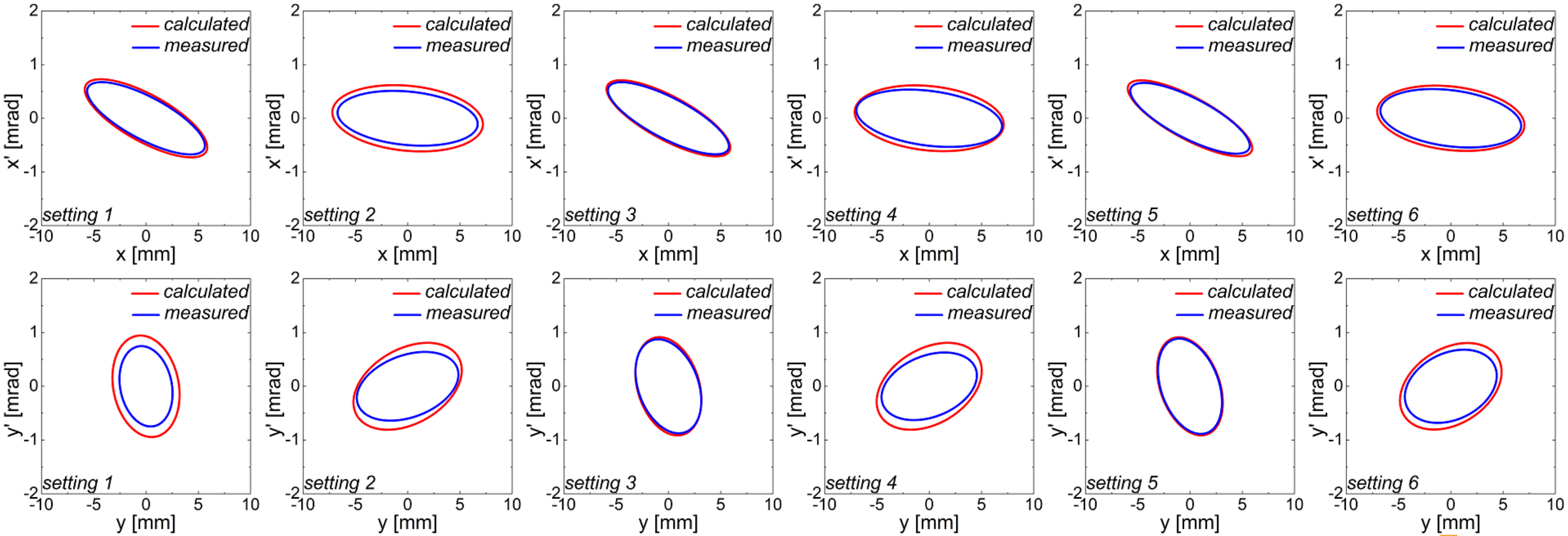
A Mathcad routine has been developed and used to minimize a so called mismatch factor in both transverse planes simultaneously. The resulting second-moment beam matrix at the entrance is:

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



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

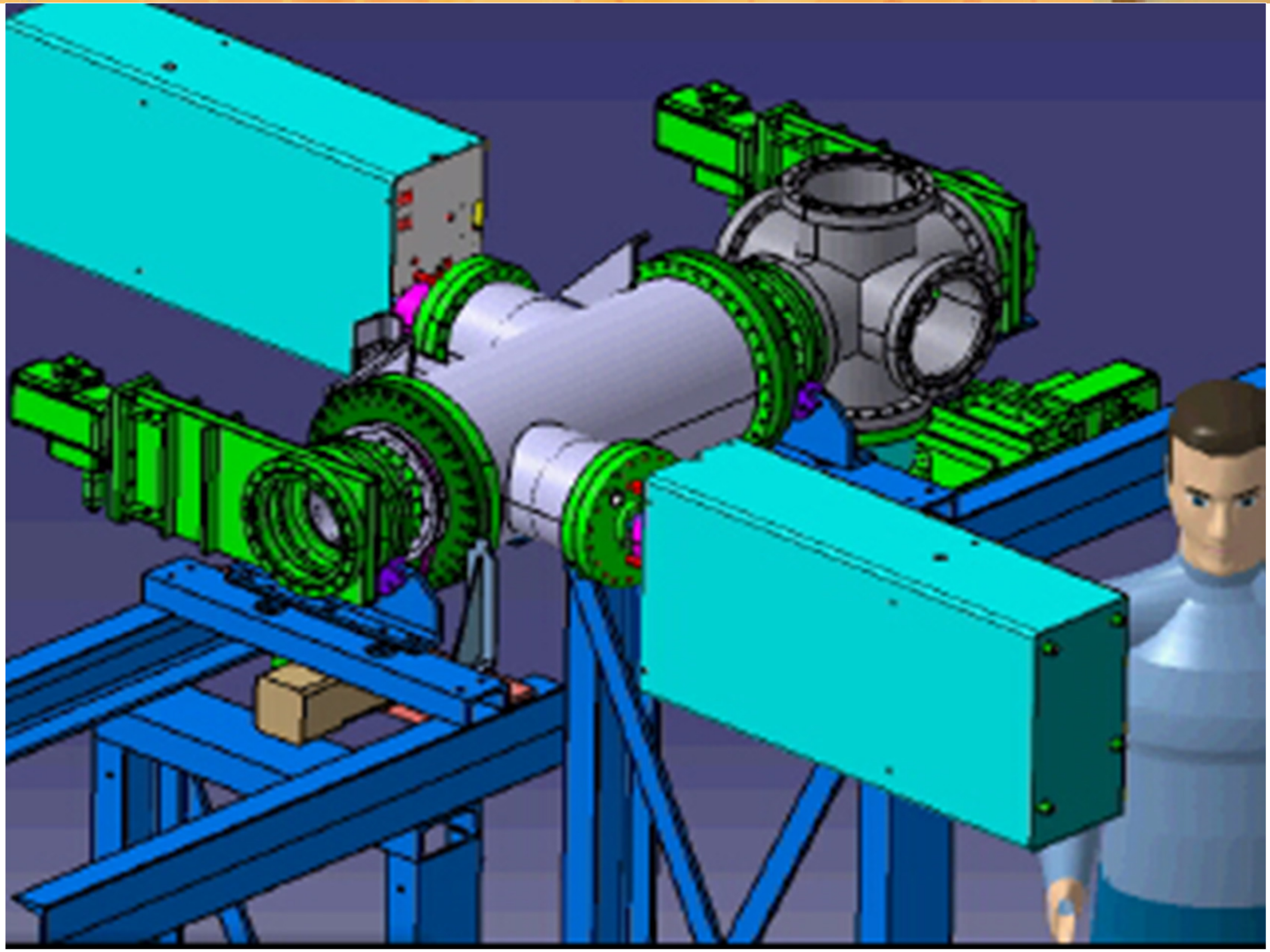
To our knowledge this is the first successful measurement of the 4D-rms-emittance using ions.
In this example, removing the correlation would allow for an increase of the beam brilliance by 75%.



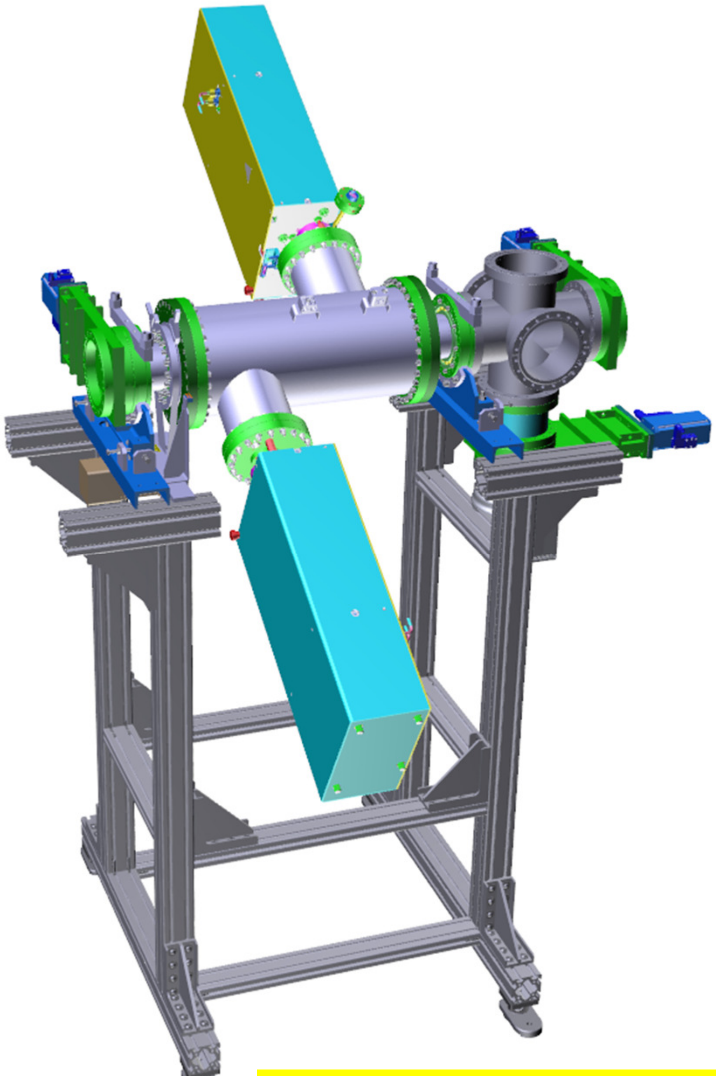
C. Xiao et al., Measurement of the transverse four-dimensional beam rms-emittance of an intense uranium beam at 11.4 MeV/u, NIMA Volume 820, p. 14-22

ROSE

Instead of rotating the beam, we could ...



ROSE
What is it and how does it work?



Bundesrepublik Deutschland

Urkunde

über die Erteilung des
Patents Nr. 10 2015 118 017

Bezeichnung:
Drehmodul für eine Beschleunigeranlage

IPC:
H05H 7/00

Inhaber/Inhaberin:
GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, DE

Erfinder/Erfinderin:
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Tag der Anmeldung:
22.10.2015

Tag der Veröffentlichung der Patenterteilung:
08.06.2017

Die Präsidentin des Deutschen Patent- und Markenamts

Cornelia Rudloff-Schäffer

Cornelia Rudloff-Schäffer

München, 08.06.2017

DEUTSCHES PATENT- UND MARKENAMT

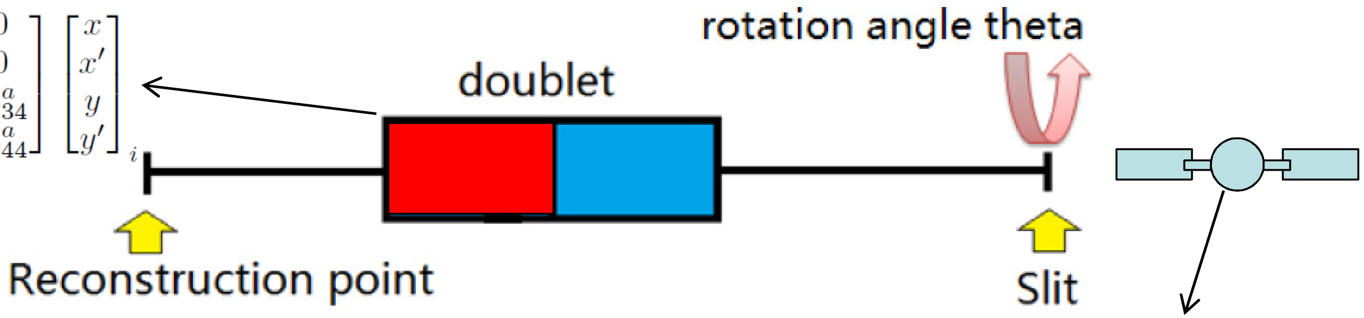
Den aktuellen Rechtsstand und Schutzumfang entnehmen Sie bitte dem DPMAregister unter www.dpma.de.

Deutsche Patentanmeldung Nr. 102015118017.0 erteilt am 08.06.2017: Drehmodul für eine Beschleunigeranlage

ROSE
The idea

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

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

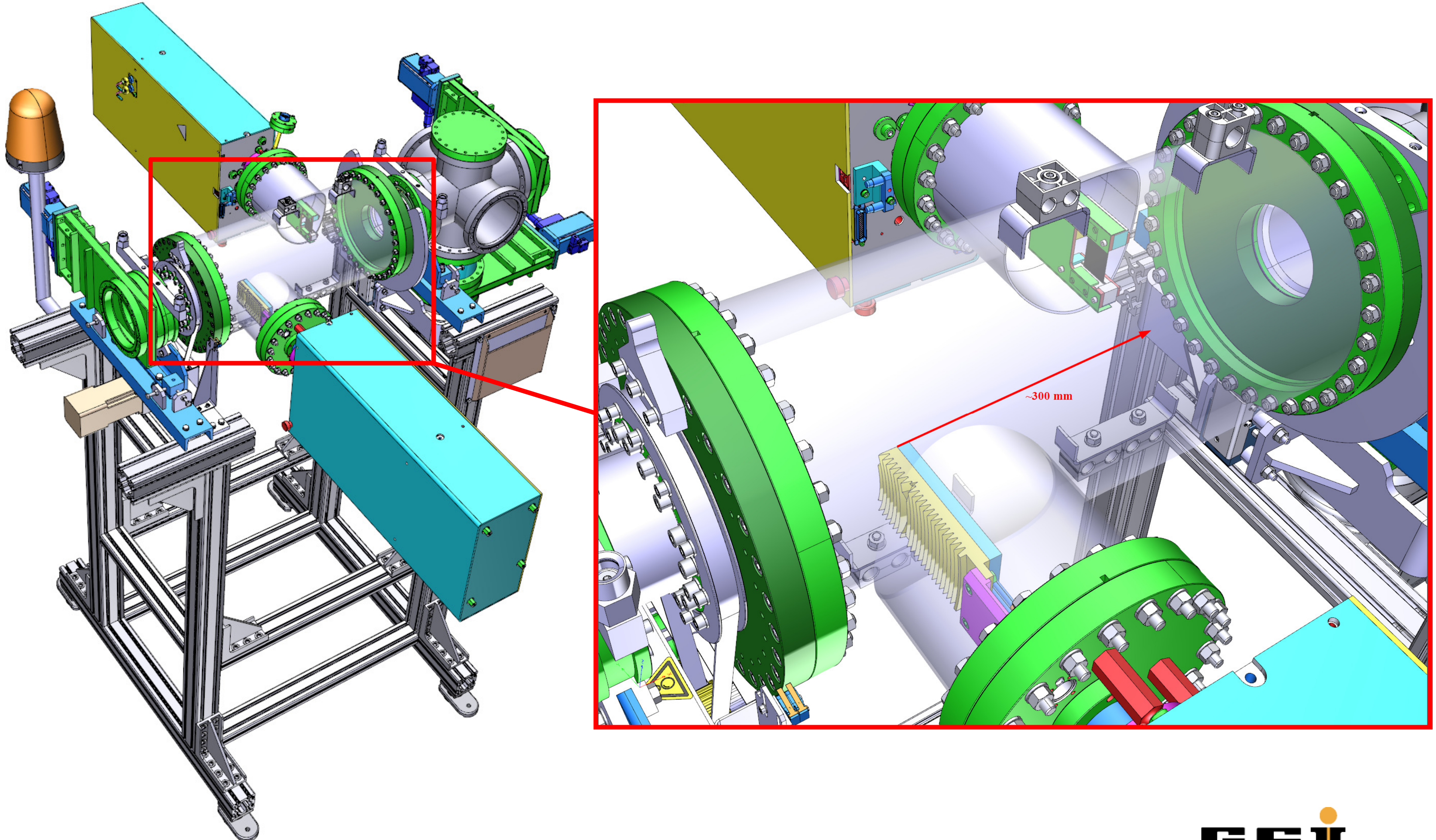
All values are measured using ROSE at the final position f. Knowing the transfer and rotation matrix they can be calculated back to the reconstruction point i, the initial position of the original not changing beam matrix C_i. 100% transmission between initial and final Position is of course required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

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

only 4 measurements are needed to measure the full beam matrix

C. Xiao, M. Maier, X. N. Du, P. Gerhard, L. Groening, S. Mickat, and H. Vormann, Phys. Rev. Accel. Beams 19, 072802 – Published 19 July 2016

Rose
technical realization

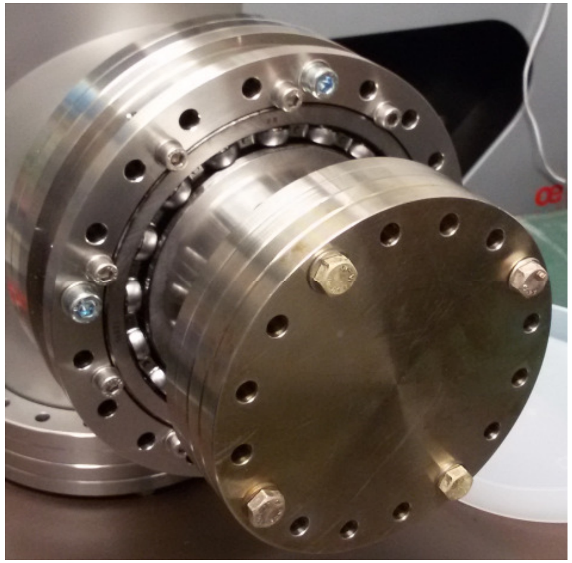


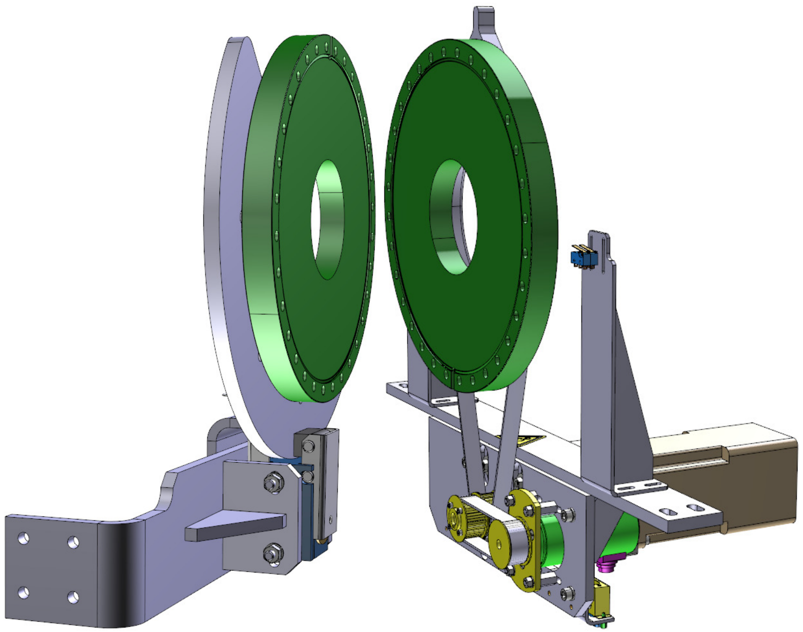
Rose
technical realization

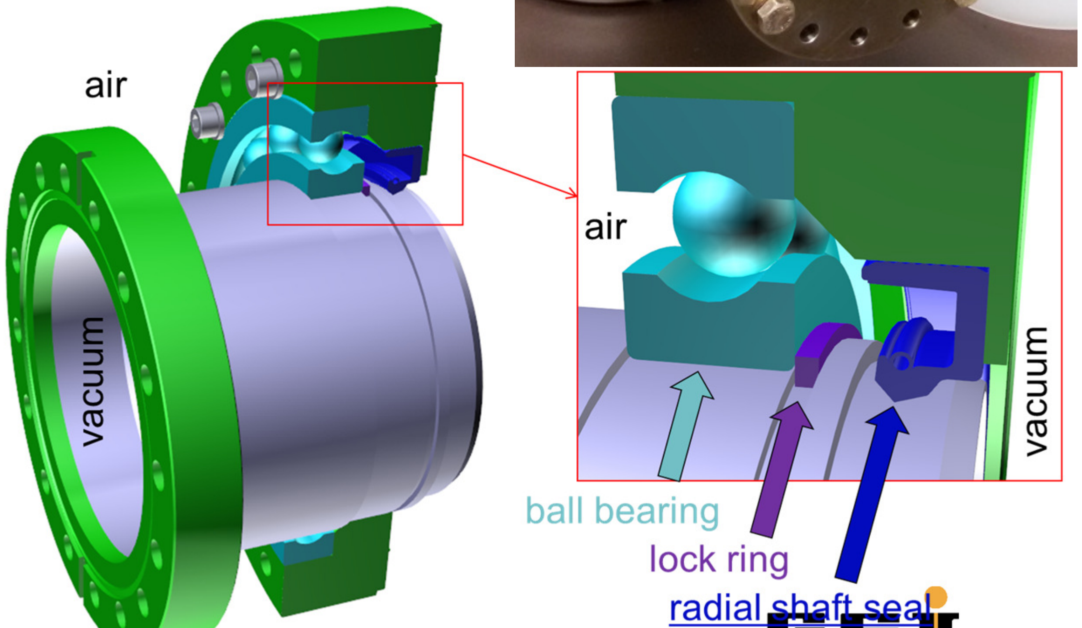
- end switches to limit the rotation if necessary
- disk brake (closed during measurements) to avoid vibrations
- motor driver with belts ($\delta\theta \leq 0.5°$)
- 90° - rotation slowed actively to ≈ 30 sec

Vacuum issues:

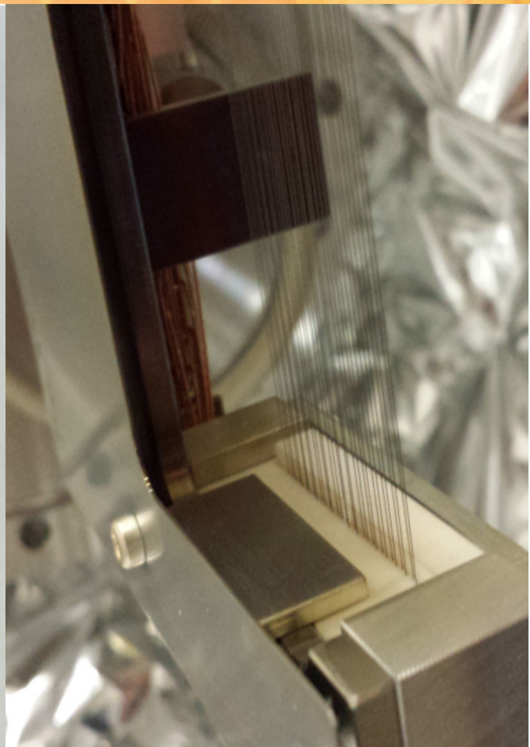
- static pressure ≈ 5×10^{-8} mbar
- max. pressure during rotation ≈ 1×10^{-7} mbar
- recovery time ≈ 1 min

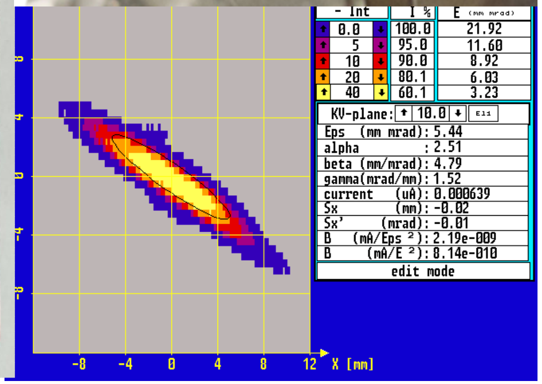




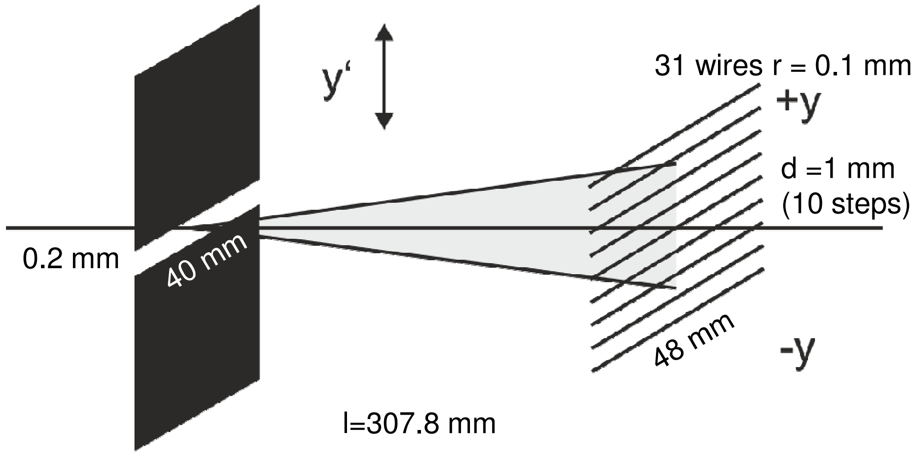


Rose
technical realization

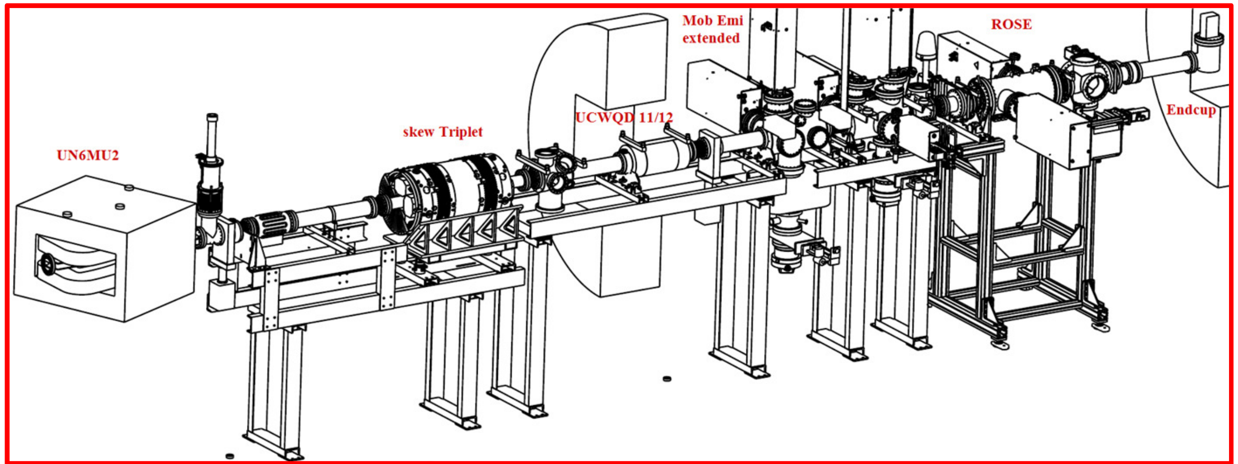




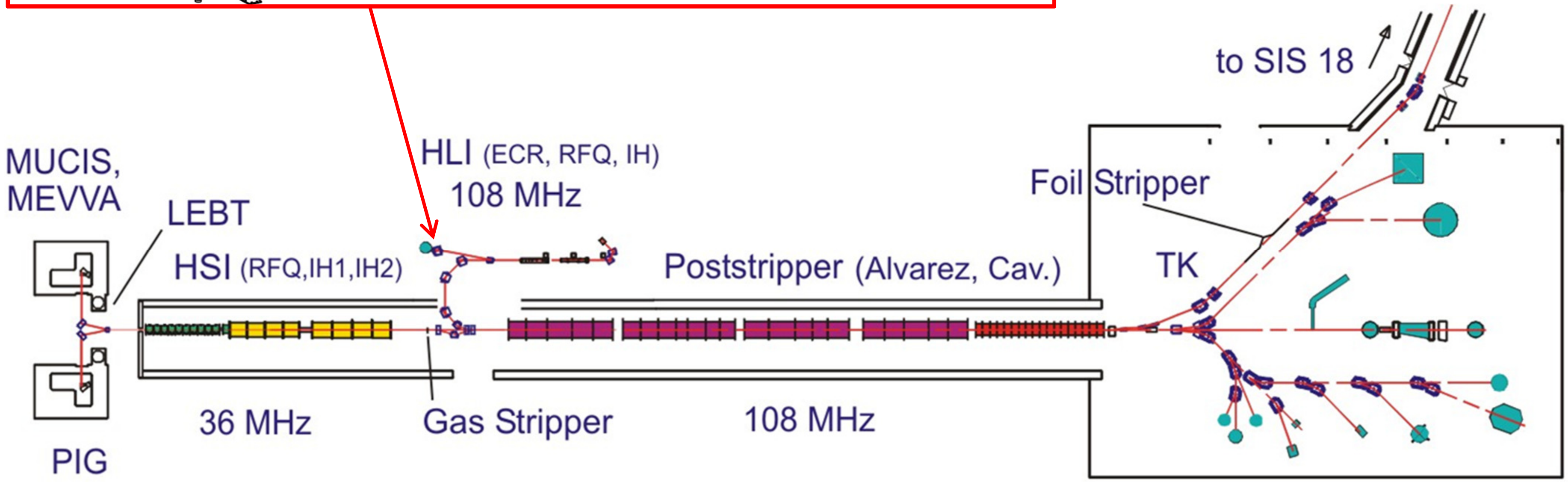
Rose maximum values:
spatial resolution 0.2 mm
angular resolution ~3.25 (0.325) mrad
beam spot size (slit) < 40 mm



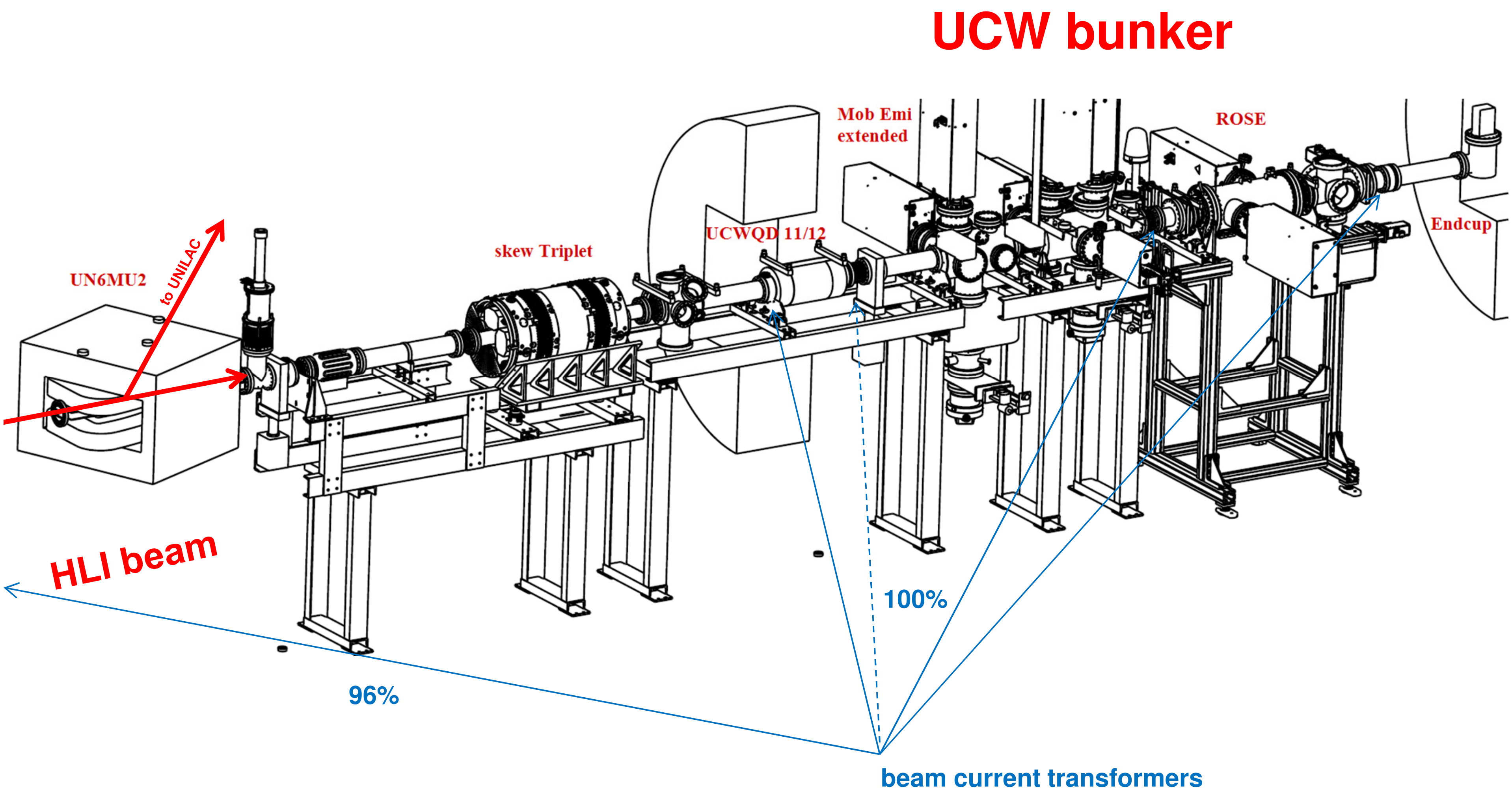
ROSE
Commissioning setup behind HLI



- 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 required



ROSE
Commissioning setup behind HLI

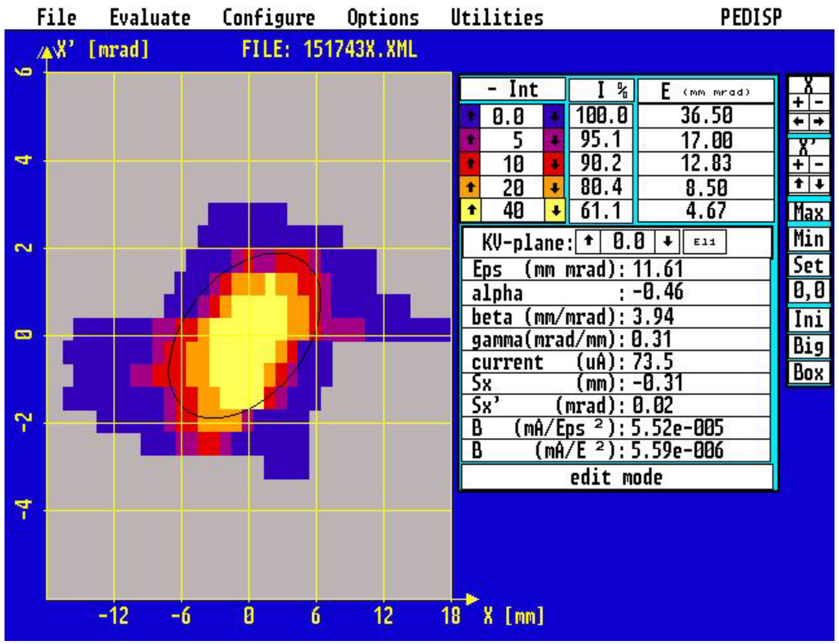


ROSE
Benchmarking against existing Emittance scanner

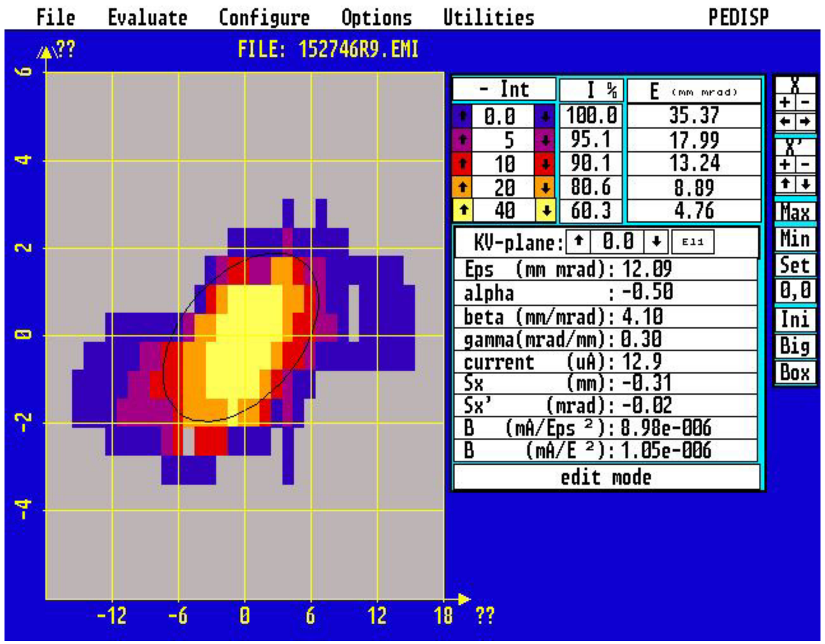
The first commissioning beam time in July 2015 using $^{40}Ar^{9+}$ mainly served to commission the hard and software of ROSE and to benchmark it against existing emittance scanners.

comparison of the horizontal Emittance using:

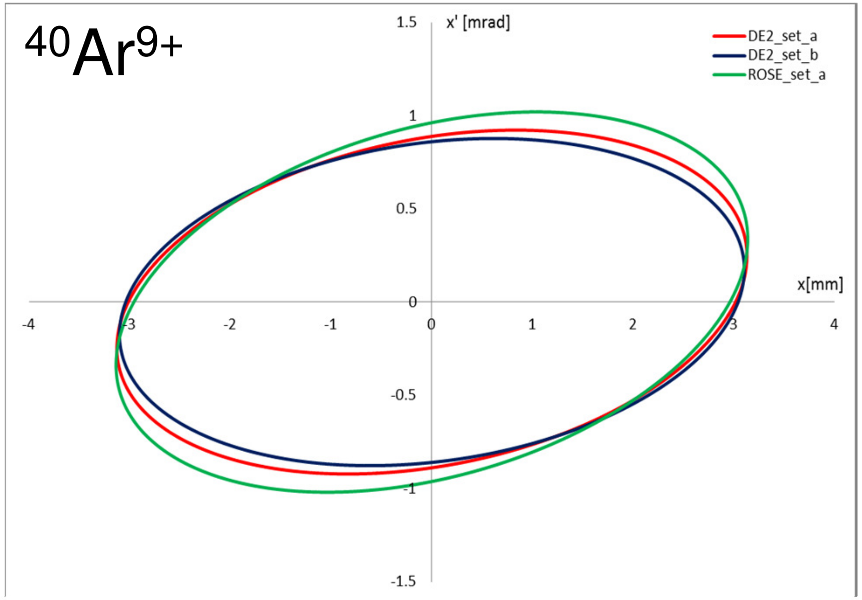
MobEmi- GUCWDE2

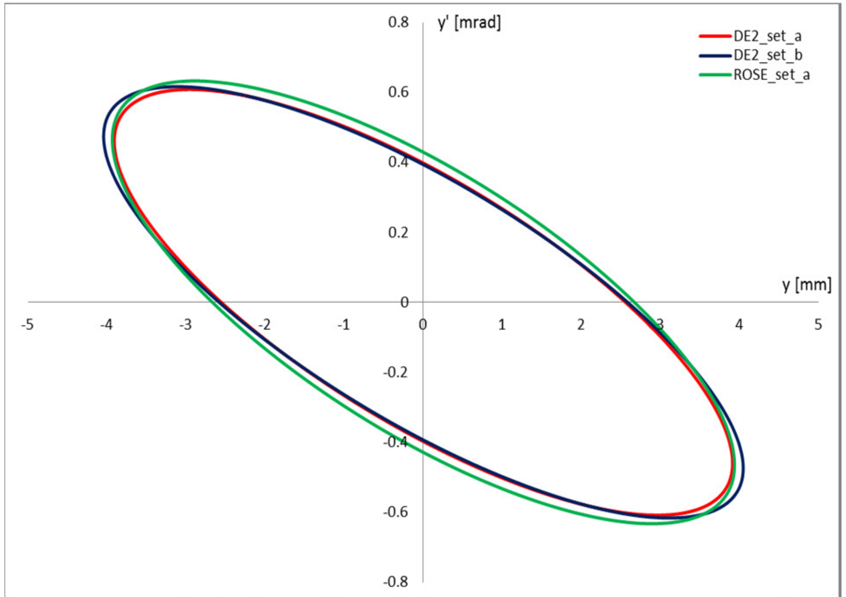


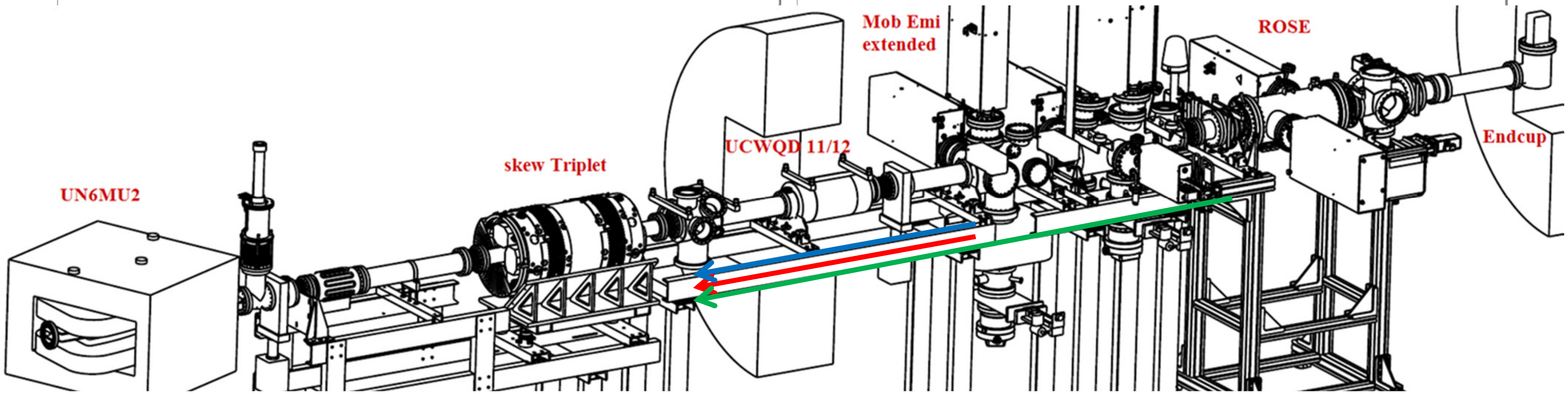
ROSE – GUCWDE4



ROSE
Benchmarking against existing Emittance scanner



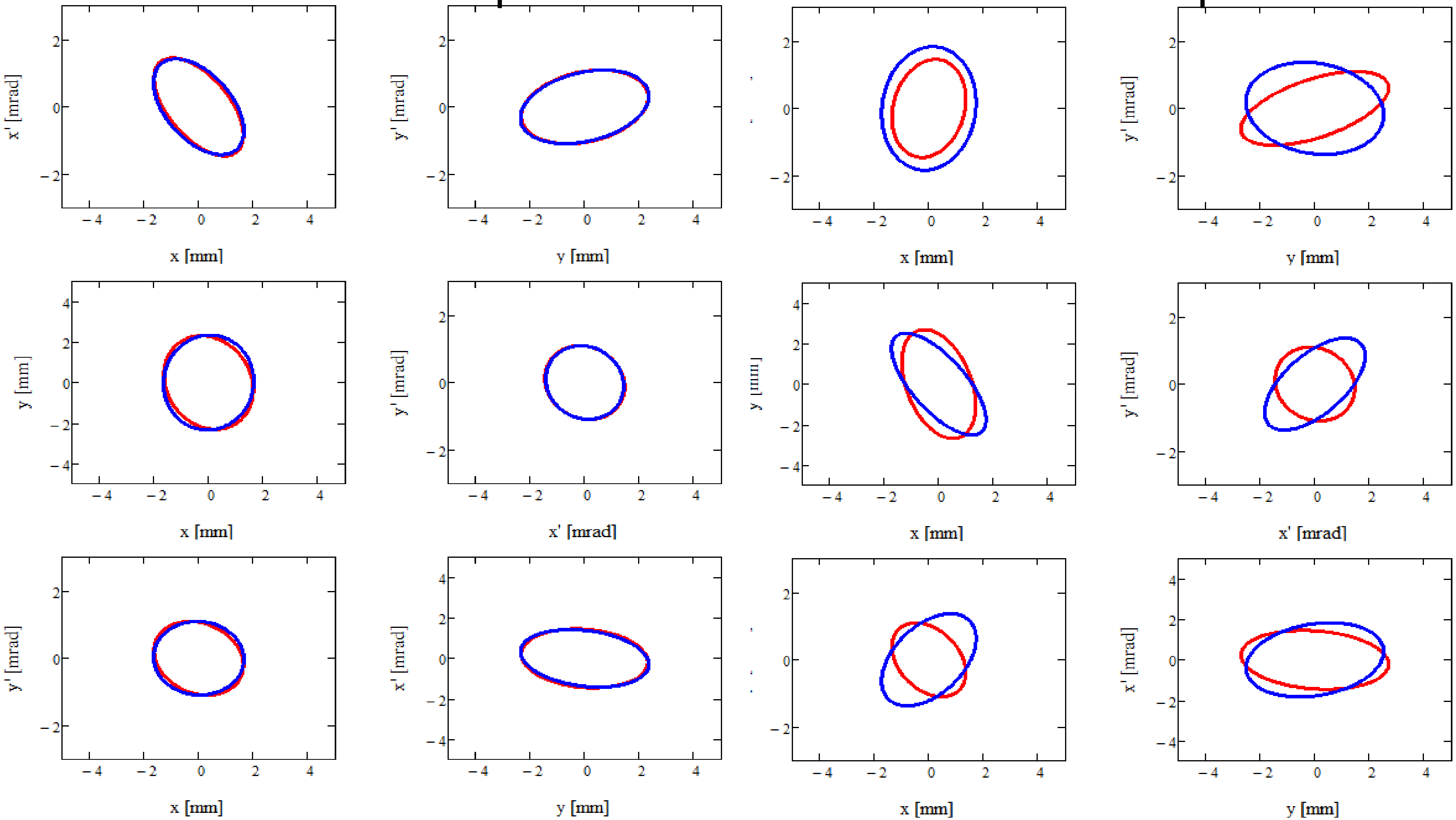




ROSE

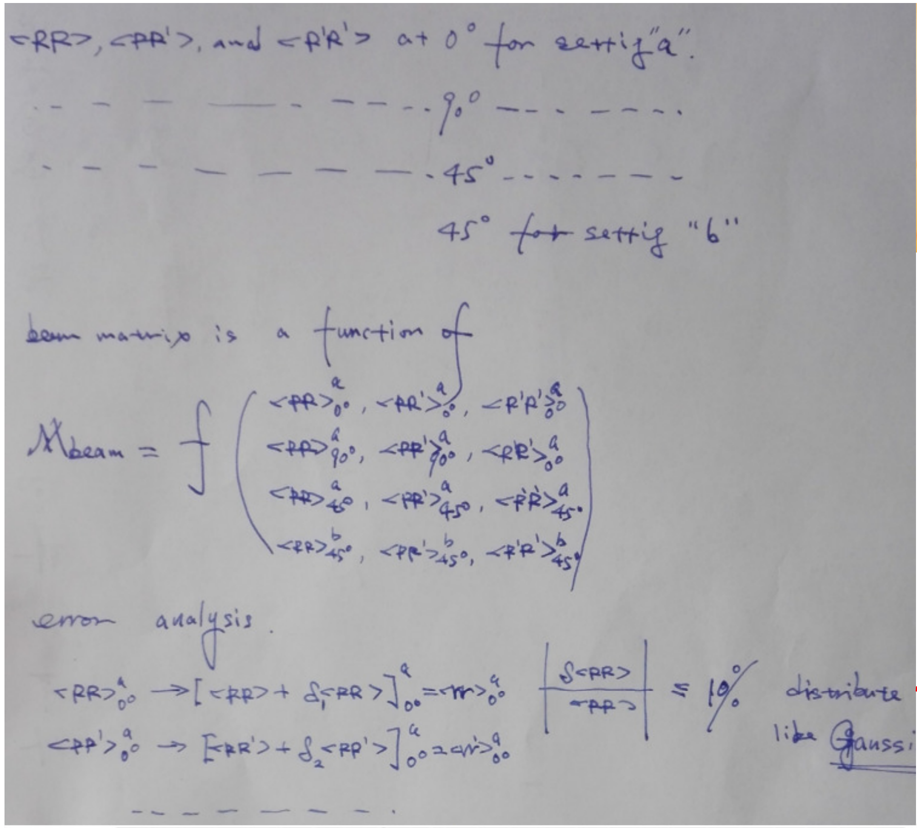
4d emittance measurement of $^{83}Kr^{13+}$

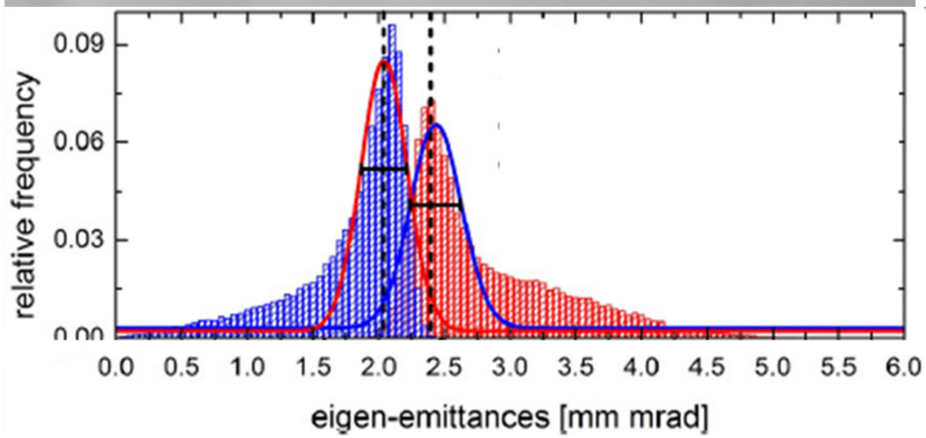
Reconstruction point i Measurement point f



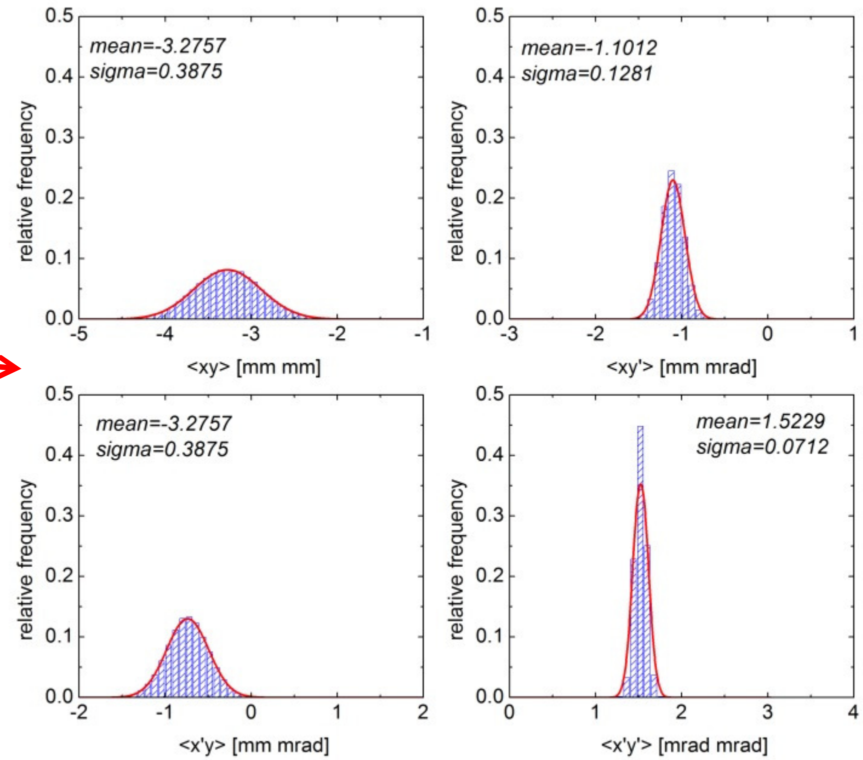
red skew off, blue skew on

Error studies



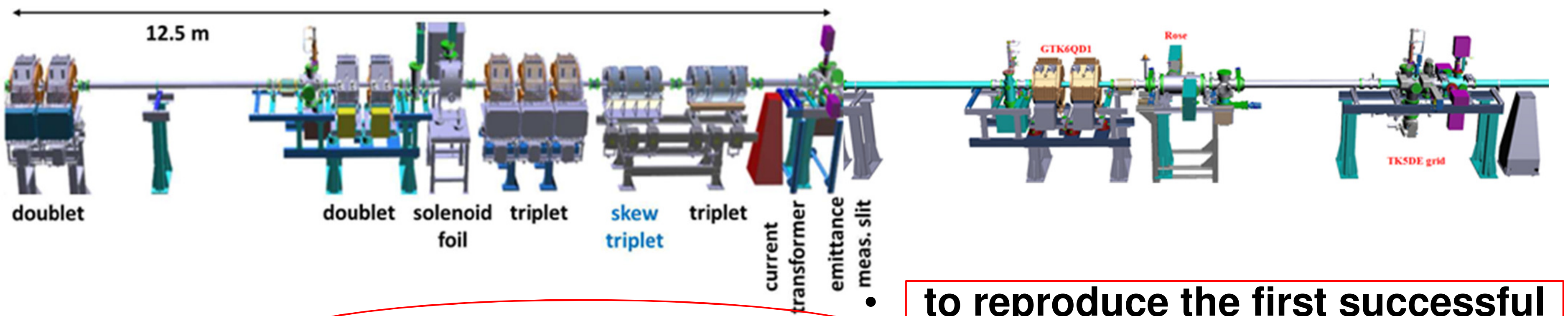


From the measured moments derived Eigen-emittances of the HLI 1.4 MeV/u $^{83}Kr^{13+}$ beam.

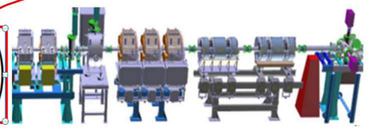


Each measured moment entering into the evaluation was varied randomly following a Gaussian distribution centered on its measured value

Rose @ TK
behind EMTEX

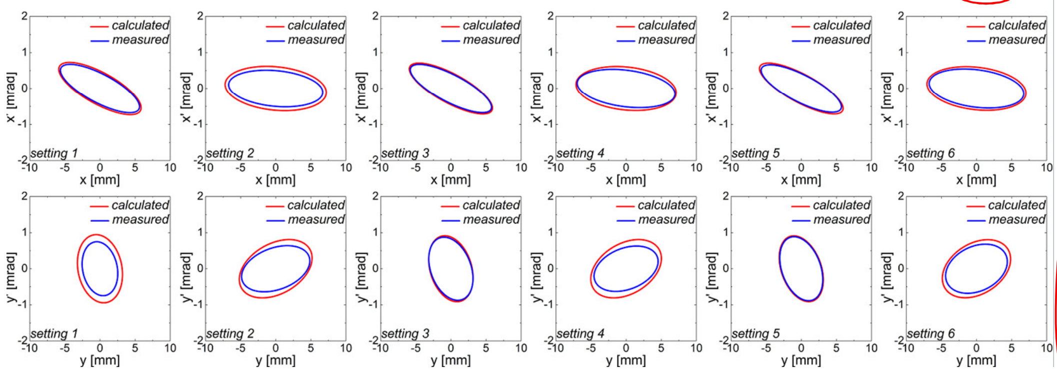


$$C'_0 = \begin{pmatrix} 12.79 & 1.89 & 0.18 & 0.37 \\ 1.89 & 0.62 & 1.69 & 0.29 \\ 0.18 & 1.69 & 32.18 & 3.49 \\ 0.37 & 0.29 & 3.49 & 0.46 \end{pmatrix}$$



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

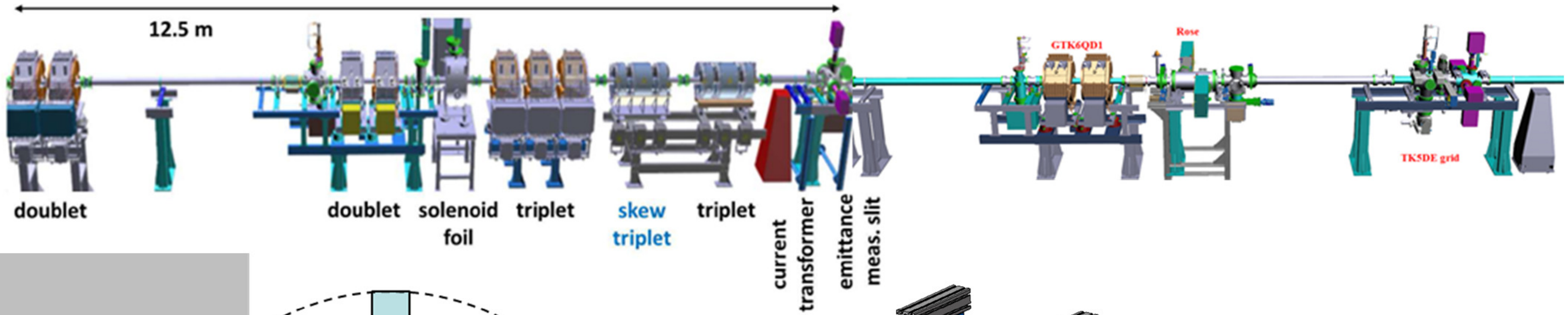
To our knowledge this is the first successful measurement of the 4D-rms-emittance using ions.
In this example removing the correlation would allow for an increase of the beam brilliance by 75%.

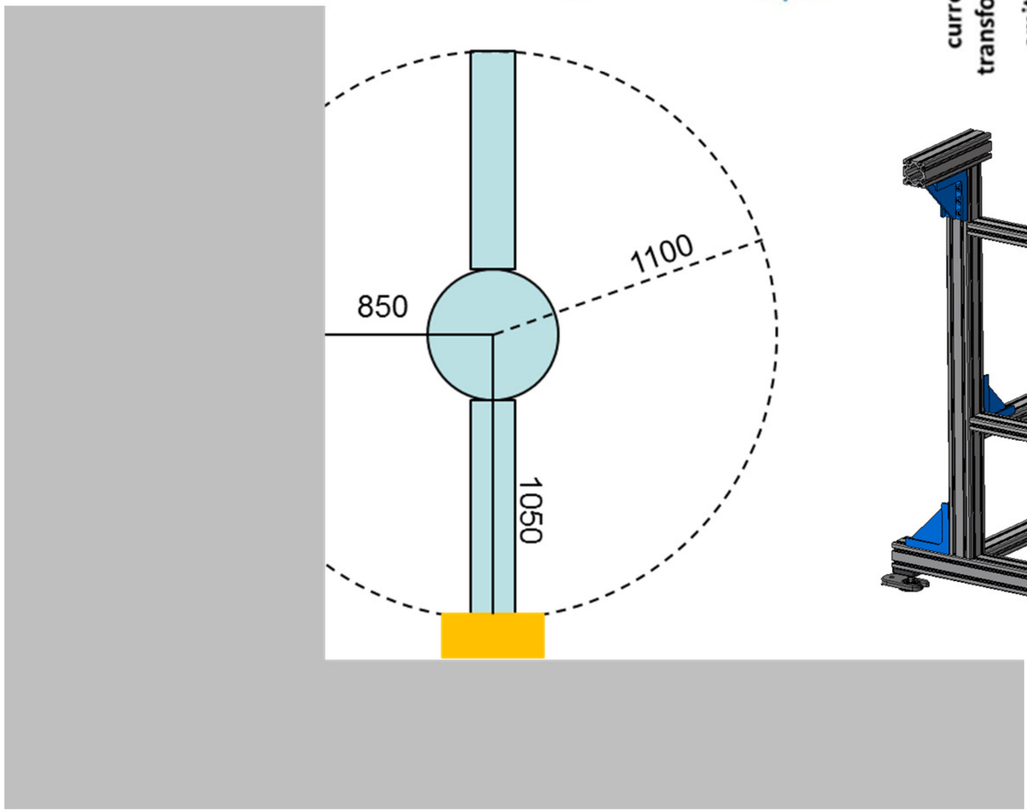


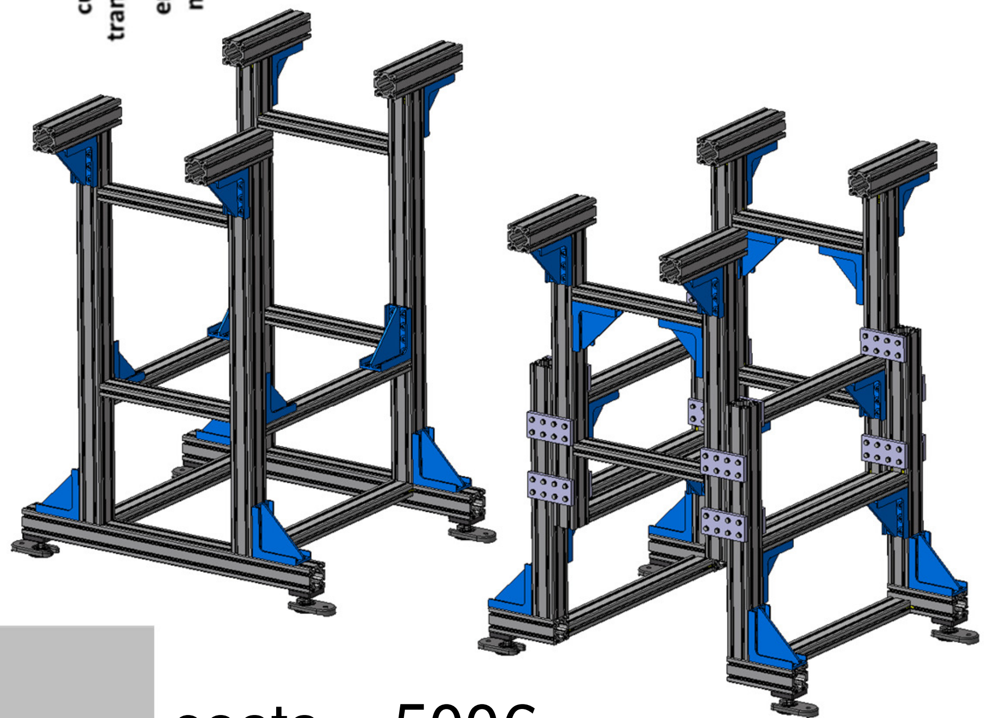
- **to reproduce the first successful measurement of the 4D-rms-emittance using ions**
- **two independent measurements of the beam coupling confirming both techniques**
- **If possible to remove the correlation and increase the beam brilliance by ~75%**

Because with Rose we do not need the skew for measuring the 4D emittance and may use it to remove the coupling!

Rose @ TK
different beamline hight

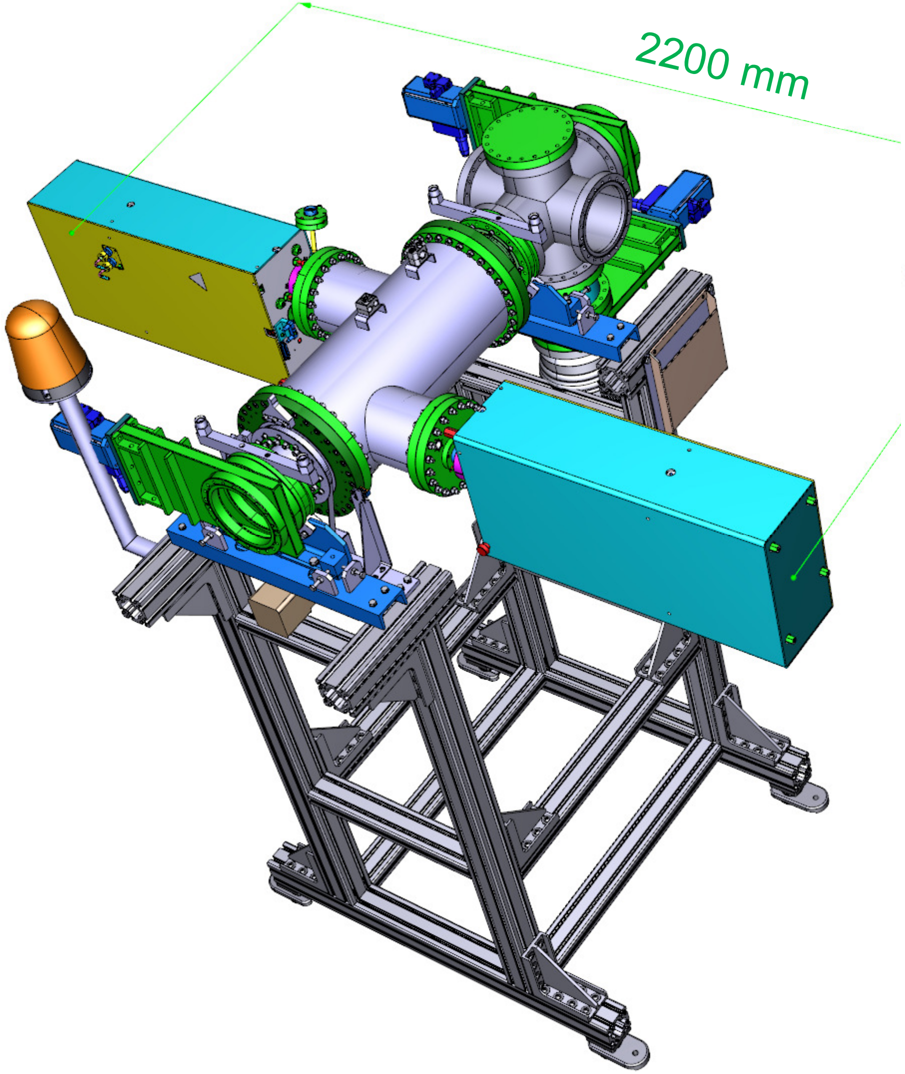


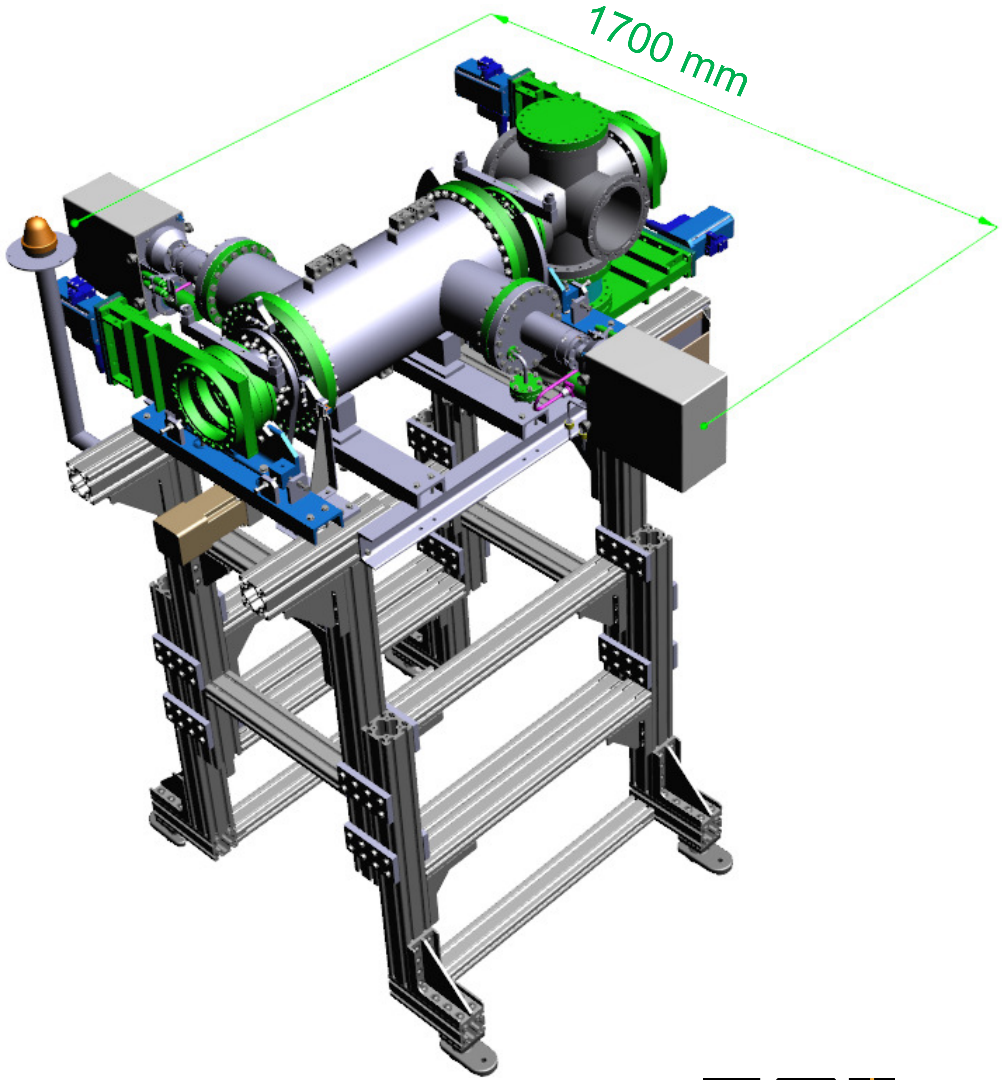




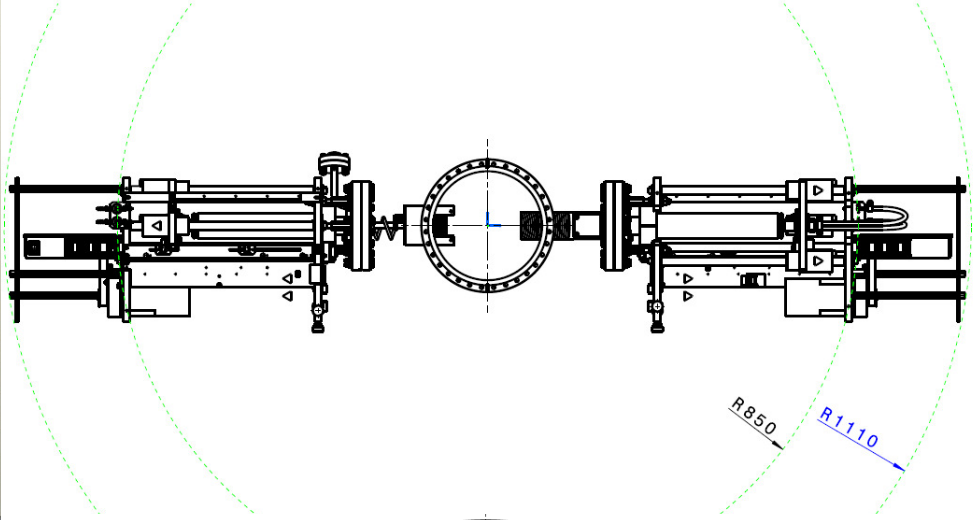
costs ~ 500€

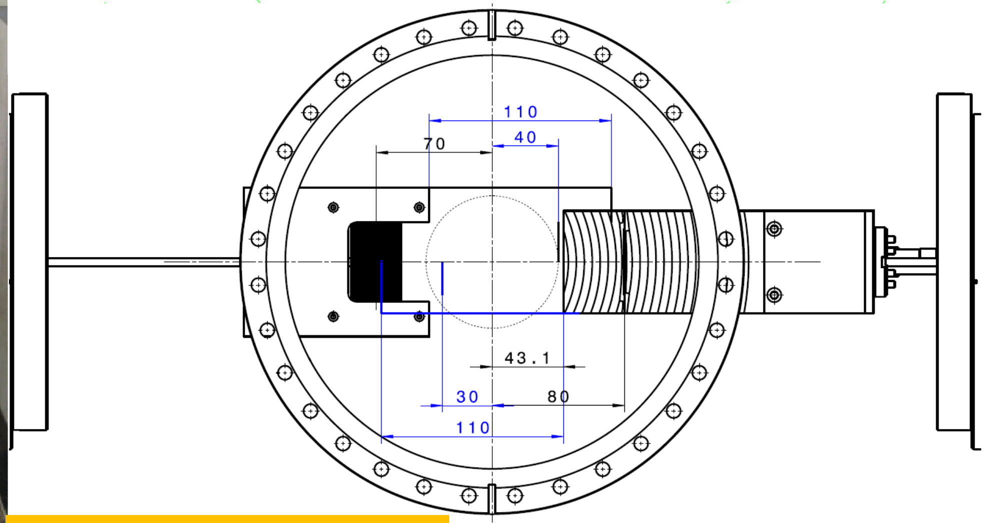
Rose behind EMTEX in the TK modifications – reduce pivoting range





Rose behind EMTEX in the TK reduce pivoting range – within specs





costs ~ 3500€

Rose @ TK
results

11.4 MeV/u 5.9 MeV/u

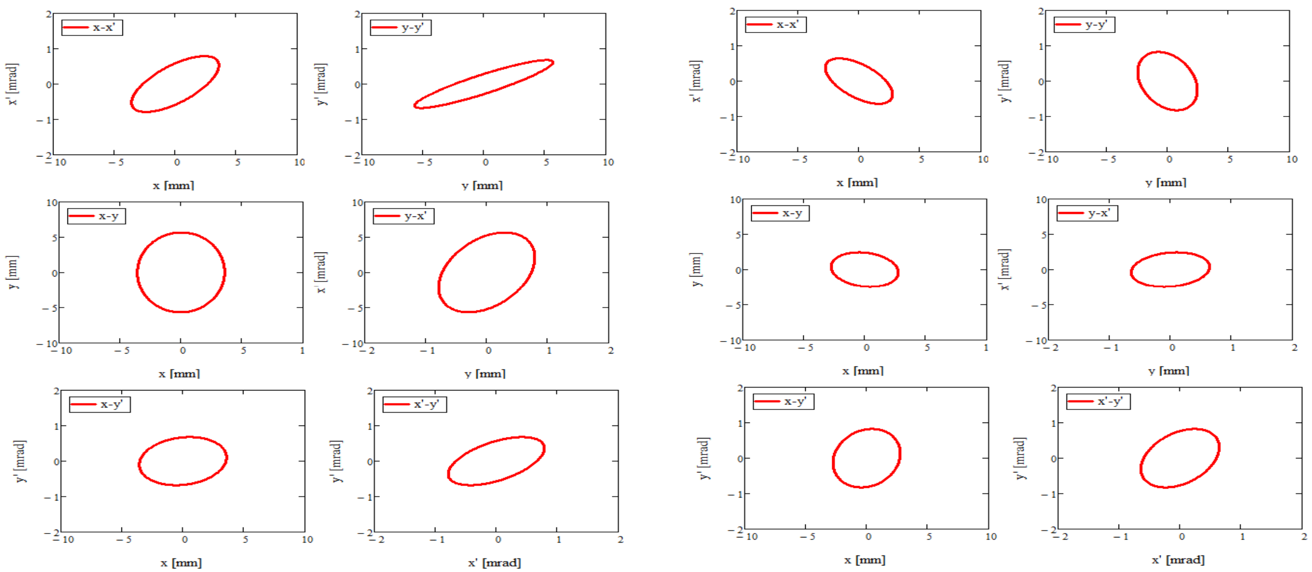


Figure 5 Measured 4d beam matrix in the transfer channel using the skew method for a $^{238}U^{28+}$ at 11.4 MeV/u (left) and using ROSE at 5.9 MeV/u (right).

	11.4 MeV/u	5.9 MeV/u
	Skew	**ROSE**
ε_x	2.1	1.94 (0.05)
ε_y	1.62	1.42 (0.04)
ε_1	2.22 (0.16)	2.07 (0.07)
ε_2	1.08 (0.12)	1.07 (0.06)
t	0.34 (0.03)	0.33 (0.05)

Because of a long breakdown of the HSI RFQ caused by a water leak in the amplifier we have lost more then 2/3 of our scheduled Uranium beam time. And anyway we were limited to an UNILAC energy of 5.9 MeV/u at the time, as the RF amplifiers of A3 were not available.

- Rose has been mechanically modified to be used in different locations, like the transfer channel.
- The method to evaluate the data, especially the error analysis has been modified and upgraded.
- We have measured the full 4D beam matrix and coupling parameters of a $^{238}U^{28+}$ beam with 5.9 MeV/u.

- The attempted main goal to remove this coupling has not been achieved, as the present skew triplet is not strong enough.
- We are planning to repeat this campaign using a lighter ion. And in case of success:
- one could think about a stronger skew triplet allowing us to decouple a Uranium beam with 11.4 MeV/u. (*75% brilliance gain?*)

Before giving an outlook lets talk about money

costs of Rose until here ~10k€ (>60k€, >500k€, >?)

money actually paid so far:			
• **external (vacuum chambers, support structure, flanges,...)**		**-**	**6500.-**
Rose goes TK:			
• Beam diagnostics changes		~	3500.-
• Support structure changes		~	500.-
Sum:		**~**	**10500.-**
billed GSI internal work:			
• Construction ~ 475 Std a 60€		-	28440.-
• mechanical workshop	-	17100.-	
• technology Laboratory		-	4860.-
Sum:			**50400.-**
Estimate of work and equipment without billing at all:			
• common systems system integration:		~	15000.-
• alignment		~	1000.-
• 1 year two full time physicists =		~	160000.-
borrowed equipment approximately worth:			
• Vacuum components (pumps, gate valves, controller, gages)		~	35000.-
• beam instrumentation (slit grid motors, controllers incl. electronics)		~	250000.-
Sum:			461000.-
Total:		**~**	**500000.-**

Outlook
Bringing ROSE to the market

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.

To sell our Rose detector system to other accelerator facilities two major developments are missing:

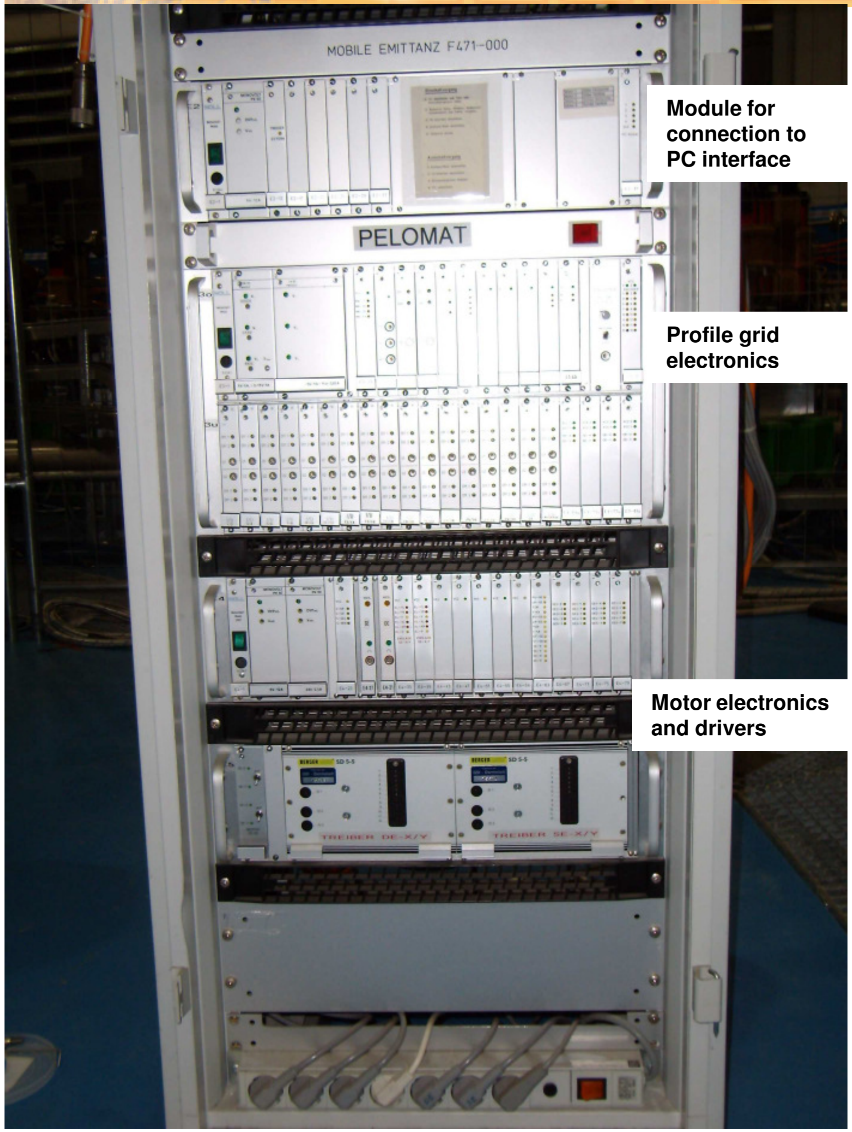
Rose needs electronics independent of the accelerator facility. Right now ROSE has no own electronics but fully relies on the GSI/FAIR backbone.

-> ROBOMAT

The expert software pool, to calculate the measurement settings, to control the movement and vacuum of the vessel, to measure the emittance and to evaluate the 4d beam matrix, needs to be combined using one usable operating GUI.

-> ROSE-SOFTWARE

Robomat
Some may remember the Pelomat



- Since mid 1990 our working horse for external emittance measurements
  - HIT, CNAO, HITRAP MPI-K, p-Linac source, ...
- Outdated beyond repair
- Not tailored to our needs (no cw mode)
- Busy most of the time

Outlook

Robomat - stand alone electronics for Rose

Beam

- p -> U: OK
- 1 keV/u -> 15 MeV/u (U) bis ~70 MeV/u (p)
- 50Hz, 10µs -> DC with grid protection option?
- 10µA -> 100mA (1µA if possible with reasonable effort)

Measurement options

- parallel mode, angle offset, diagonal mode, double grid mode
- up to 10 intermediate grid steps to increase angular resolution
- combinations of mode and intermediate steps
- measurement range automatic (de-slow) or manual (de-fast)
- ultrafast mode: drive by data taking - continuous drive and data taking
- Background measurement wo beam stored separately
- pure profile grid measurement (grid protection)

Hardware used in Rose

- Oriental 5 phase motors Type: A717-9415KM
- Oriental motor driver: CRD512PB
- TWK Encoder Typ: : TWK CM 50-1024 G18 A01 (Gray Code 18 Bit parallel Schnittstelle)
  - Alternative1: TWK CM 50-1024 G18 E01 (SSI Schnittstelle)
  - Alternative2: linear potentiometer 2 -10 kOhm

Hardware requirements and options for electronic (open collection):

- Pyramide IU Wandler F3200E <1nA - 10mA bipolare Eingänge DC -250 kHz
- Pyramide Software PTC Diagnostic P2
- Control unit, for Profilgrid and motion control
- Connectors and pin assignment, according to our specifications
- Endswitches (double* or other solution)
- Interlock capability (beam block moving device, vacuum interlock, grid protection)
- rack big enough to include emittance and vacuum controls
- minimum step size 0.1mm (grid wire diameter)
- A beam current measurement (see xml file: trafocurrent) in front of Rose should be included
- To ensure 100% transmission there needs to be a beam current monitor behind ROSE as well
- Possibility to control the beam current in realtime (GSI: PG Schutz Pulsverkürzung Chopper)

Software and data format

- For evaluation we will use the new PROEMI (JAVA based)
- original data saved as .XML files

XML example:

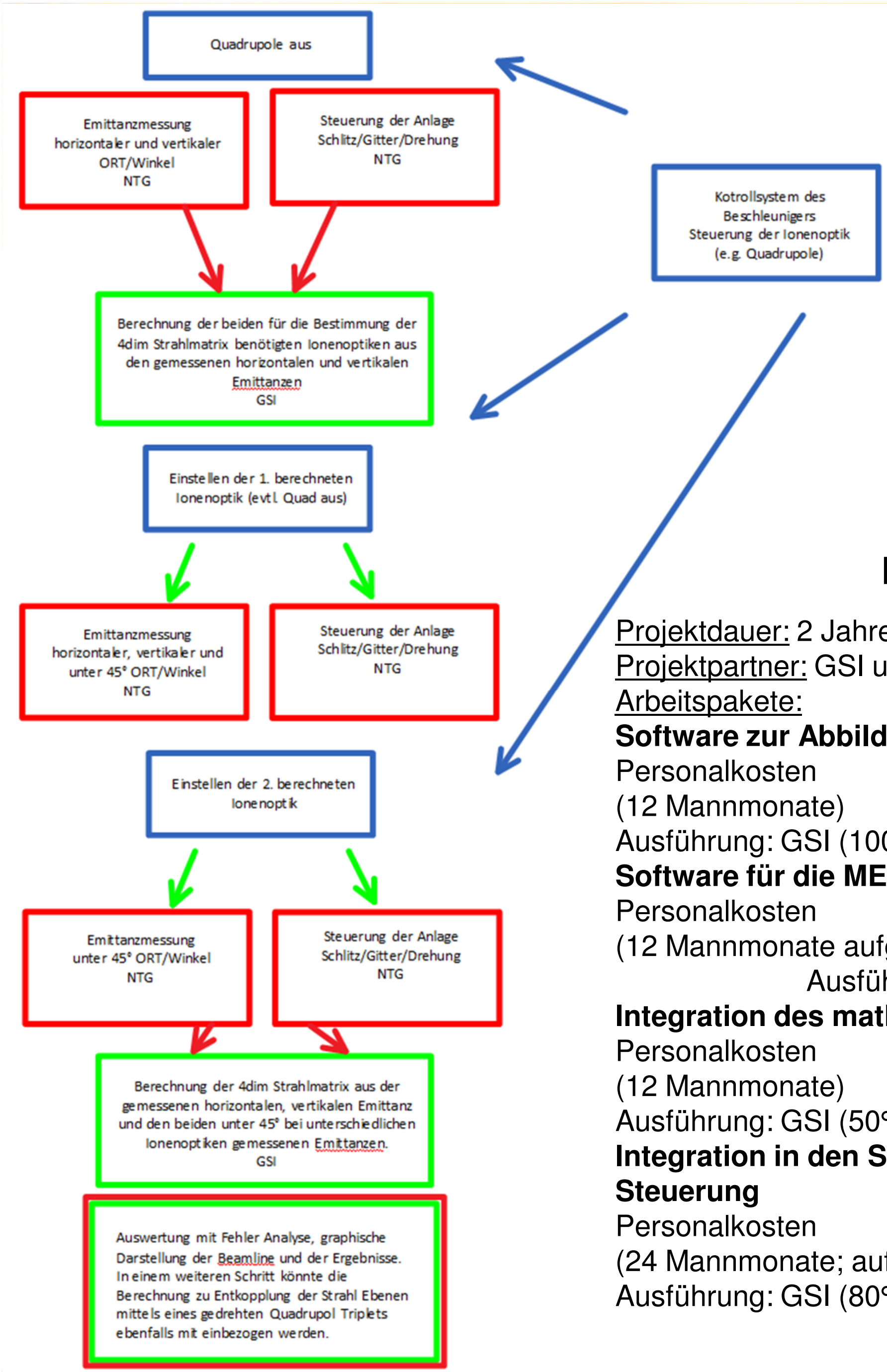
Robomat will be built by NTG according to our specifications, that have been developed together with the beam diagnostics group at GSI.
costs ~ 120 k€ of which 84 k€ are a WIPANO grant.*

Key issues:
- Stand alone emittance scanner electronics.
- CW and pulsed beam operation.
- Allowing all specified measurement options.
- Output of the measurement raw data as XML.

Project start was the 01.01.2018 and we are expecting the SAT at the HIT facility in autumn 2018.

* Special thanks to TTF for their support

Outlook
Rose Software package

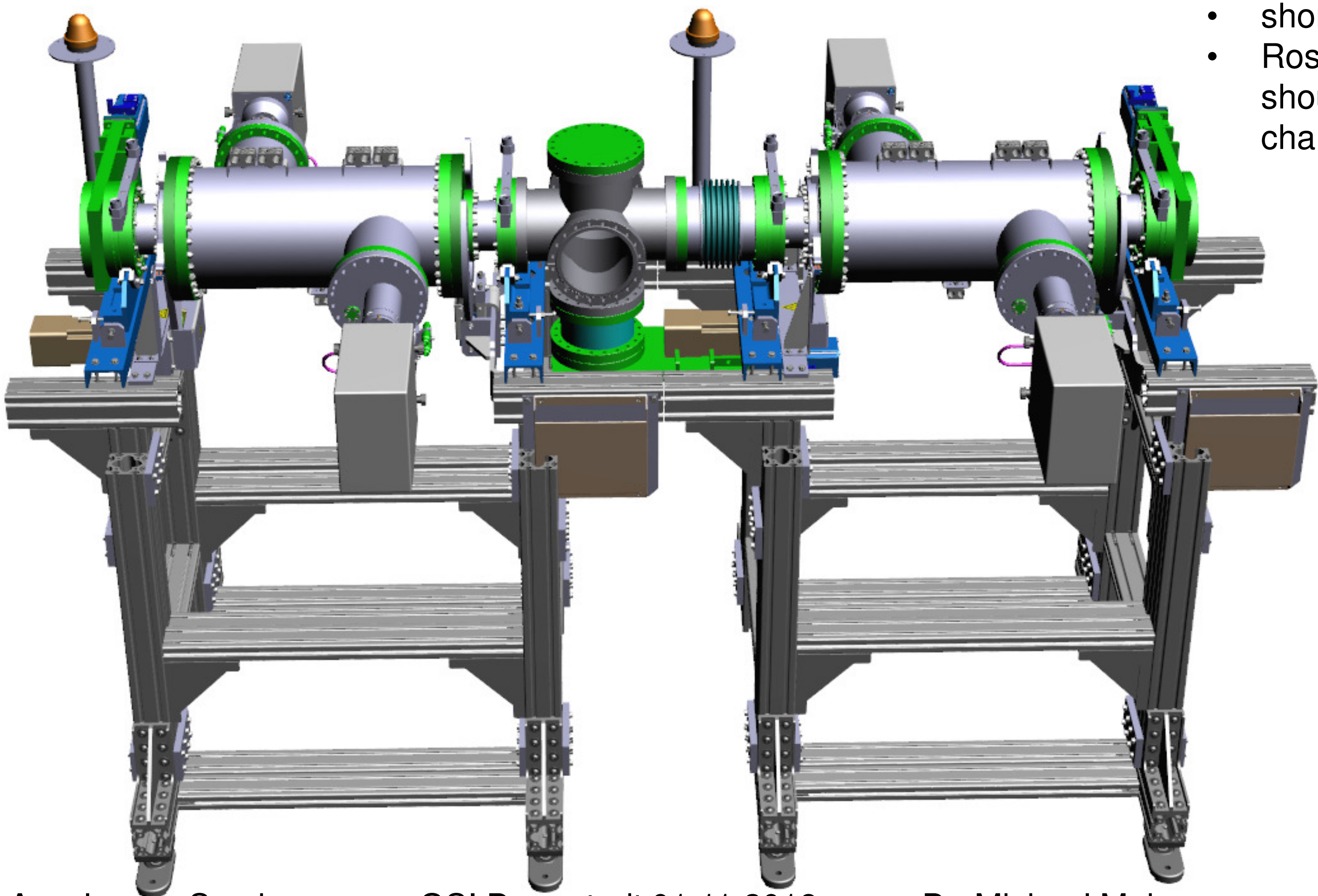


- ROBOMAT includes ε software
- 4d matrix formalism
- General accelerator input

Projektskizze
Rotating **S**ystem for 4D-**E**mittance Scans (**ROSE**)

Projektdauer: 2 Jahre
Projektpartner: GSI und NTG Neue Technologien GmbH & Co. KG
Arbeitspakete:
Software zur Abbildung/Optimierung des MATHEMATISCHEN MODELLS
Personalkosten 80.000 €
(12 Mannmonate)
Ausführung: GSI (100%)
Software für die MENSCH-MASCHINE-SCHNITTSTELLE (Usability)
Personalkosten 80.000 €
(12 Mannmonate aufgeteilt auf 2 Mitarbeiter)
Ausführung: NTG (100%)
Integration des mathematischen Modells in die Mensch-Maschine-Schnittstelle
Personalkosten ca. 80.000 €
(12 Mannmonate)
Ausführung: GSI (50%) und NTG (50%)
Integration in den Strahl und Testung des ZWEI-KAMMER-SYSTEMS und dessen Steuerung
Personalkosten ca. 80.000 €
(24 Mannmonate; aufgeteilt auf 2 Mitarbeiter GSI & 6 Mannmonate 1 Mitarbeiter NTG)
Ausführung: GSI (80%) und NTG (20%)

Outlook
optimizing mti into SIS using **ROSEs** @ TK



- Still dreaming of the 75% brilliance gain for $^{238}U^{28+}$
- higher resolution
- shorter measurement times
- Rose as an industrial product should definitely be a two chamber system

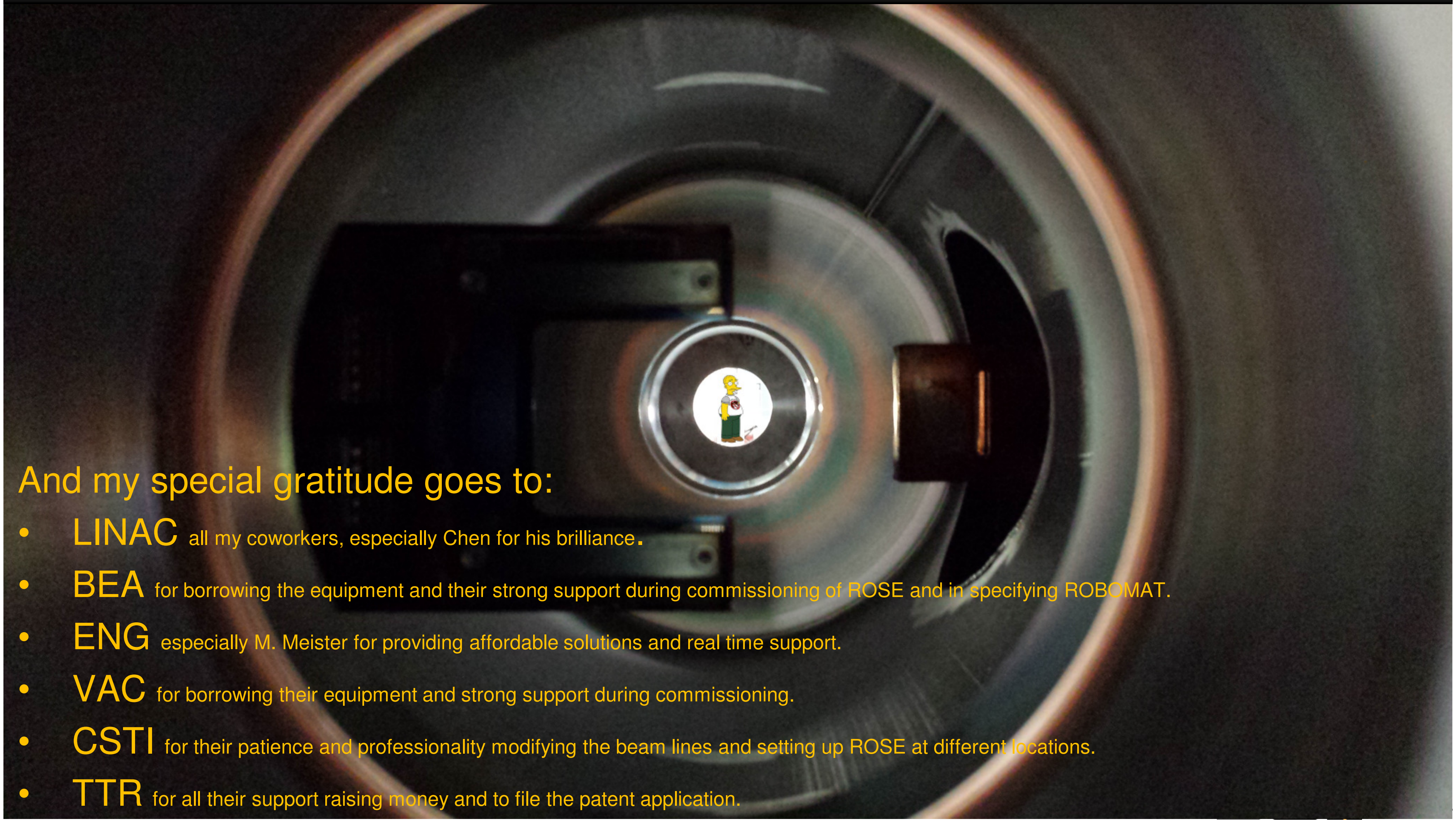
Summary

A new method, using an rotatable slit/grid emittance measurement device called ROSE, has been developed and commissioned to measure the four-dimensional second order beam matrix. It will allow fast and mobile four-dimensional emittance measurements without additional elements. This unique set-up works with highest reliability.

ROSE can provide as major deliverable the optics to fully decouple a correlated beam.

The main objective right now is to develop a turnkey 4d emittance scanner for the ion accelerator community and with NTG Neue Technologien GmbH & Co. KG we have found an industrial partner and are successfully raising funds for this project.

Thank you for your attention



And my special gratitude goes to:

- LINAC all my coworkers, especially Chen for his brilliance.
- BEA for borrowing the equipment and their strong support during commissioning of ROSE and in specifying ROBOMAT.
- ENG especially M. Meister for providing affordable solutions and real time support.
- VAC for borrowing their equipment and strong support during commissioning.
- CSTI for their patience and professionality modifying the beam lines and setting up ROSE at different locations.
- TTR for all their support raising money and to file the patent application.