# COMPLETE TRANSVERSE 4D BEAM CHARACTERIZATION FOR ION BEAMS AT ENERGIES OF FEW MeV/U

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*Abstract*

Measurement of the ion beam rms-emittances is done through determination of the second order beam moments. For time being the moments quantifying the amount of inter-plane coupling, as <xy> for instance, have been accessible to measurements just for very special cases of ions at energies below 150 keV/u using pepper pots. This contribution presents successful measurements of all inter-plane coupling moments at 1 to 11 MeV/u. From first principles the used methods are applicable at all ion energies. The first campaign applied skewed quadrupoles in combination with a regular slit/grid emittance measurement device. The second campaign used a rotatable slit/grid device in combination with regular quadrupoles.

## INTRODUCTION

Usually just separated measurements of two-dimensional x-x′ and y-y′ sub phase-spaces (planes) are measured, as for simplicity correlations between the two planes, i.e. x-y, x-y′, x′-y, and x′-y′ are often assumed as zero. However, such inter-plane correlations may be produced by non-linear fields such as dipole fringes, solenoids, and titled magnets or just by beam losses. Figure 1 shows the simulation of a coupled and an uncoupled beam with initially identical projected horizontal and vertical rms-emittances though a solenoid channel. This illustrates the fact that initial coupling influences the final horizontal and vertical beam size.

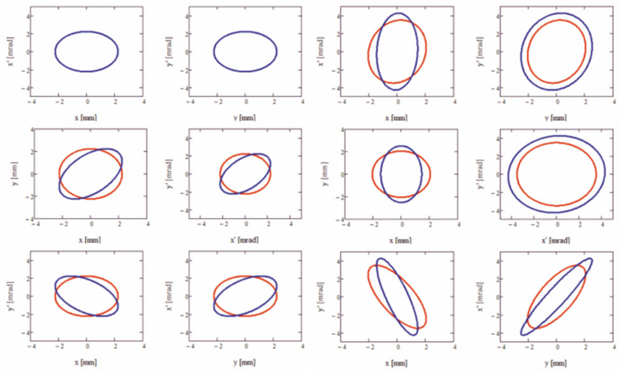


Figure 1: Simulations of an initially uncoupled (red) and coupled (blue) ion beam (left) through a solenoid channel (right).

For some applications [1], to match the round transverse phase space of a Linac beam to the flat acceptance of a synchrotron, inter-plane correlations are a prerequisite. In order to remove correlations that do increase the projected rms-emittance, they must be quantified by measurements.

There is considerable work on measuring four-dimensional distributions using pepper-pots [2-5] for electron beams or ion beams at energies below 150 keV/u, where the beam can be stopped by the pepper-pot mask. However, due to technical reasons this method is not applicable at energies above 150 keV/u, i.e. doubtful readout by temperature-dependent screens and fixed resolutions by holes and screens [6]. In the following we report about the combination of skew quadrupoles with a slit/grid emittance measurement device [7] and on ROSE [8],[9] an alternative method to measure the full 4d beam matrix that additionally features a significantly reduced time needed to perform the measurements.

## FOUR-DIMENSIONAL RMS-QUANTITIES

The four-dimensional second-moments beam matrix contains ten unique elements, four of which describe the coupling.

$$C = \begin{bmatrix} XX & XX' & XY & XY' \\ X'X & X'X' & X'Y & X'Y' \\ YX & YX' & YY & YY' \\ Y'X & Y'X' & Y'Y & Y'Y' \end{bmatrix} \quad (1)$$

If at least one of the elements of the off-diagonal submatrix is non-zero, the beam is x–y coupled. Projected rms-emittances $\varepsilon_x$ and $\varepsilon_y$ are quantities which are used to characterize the transverse beam quality in the laboratory coordinate system and are invariant under linear uncoupled (with respect to the laboratory coordinate system) symplectic transformations. Projected rms-emittances are the rms phase-space areas from projections of the particle distribution onto the planes, and their values are equal to the square roots of the determinants of the on-diagonal submatrices, i.e., phase-space area divided by π:

$$\varepsilon_\mu = \sqrt{<\mu\mu><\mu'\mu'> - <\mu\mu'>^2}\ , \quad (2)$$

where μ refers to either x or y. The dimensionless parameter α relates to the μ−μ′ correlation and the β-function refers to the beam width. They are defined as

$$\alpha_\mu = -\frac{<\mu\mu'>}{\varepsilon_\mu}, \beta_\mu = \frac{<\mu\mu'>}{\varepsilon_\mu}\ . \quad (3)$$

The Eigen-emittances $\varepsilon_1$ and $\varepsilon_2$ are invariant under coupled linear symplectic transformations provided by solenoids and skew quadrupoles for instance [10] . None of the projected emittances can be smaller than the smaller of the two Eigen-emittances. The Eigen-emittances $\varepsilon_{1,2}$ can be expressed as [9].

$$\varepsilon_1 = \frac{1}{2}\sqrt{-tr[(CJ)^2] + \sqrt{tr[(CJ)^2] - 16\det(C)}} \quad (4)$$

$$\varepsilon_2 = \frac{1}{2}\sqrt{-tr[(CJ)^2] - \sqrt{tr[(CJ)^2] - 16\det(C)}} \quad (5)$$

The square matrix J is the skew-symmetric matrix with non-zero entries in the block diagonal off form and is defined as:

$$J = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \end{bmatrix} \tag{6}$$

If the second-moments beam matrix (see Eq. (1)) has correlations between the horizontal and vertical phase-spaces, the Eigen-emittances and projected rms-emittances are different. The four-dimensional beam rms- emittance is calculated as

$$\varepsilon_{4d} = \varepsilon_1 \varepsilon_2 = \sqrt{detC} \tag{7}$$

The coupling parameter t is introduced to quantify the inter-plane coupling as

$$t = \frac{\varepsilon_x \varepsilon_y}{\varepsilon_1 \varepsilon_2} - 1 \geq 0 \tag{8}$$

If it is equal to zero, there is no inter-plane correlations and the projected rms-emittances are equal to the Eigen-emittances. The beam brilliance, another figure of merit for a beam quality especially for injectors, is defined as

$$B = \frac{I}{\varepsilon_x \varepsilon_y} = 1 \frac{I}{(1+t)\varepsilon_1 \varepsilon_2} \tag{9}$$

## SKEW QUADRUPOLE VARIATIONS

For the schematically sketched experiment [7] in Fig. 2 a beam of $^{238}U^{28+}$ at 11.4 MeV/u at a pulse current of 1.7 emA was used. The measured beam current transmission through this section was 95%. The entrance of this beam line is referred to as location *i* and the slit location is referred to as location *f*. The first measurement is done with skew quadrupoles being switched-off (uncoupled lattice) and emittances were measured in both planes. The obtained beam moments together with the settings of regular quadrupoles are used to determine the beam parameters at the entrance through back-transportation

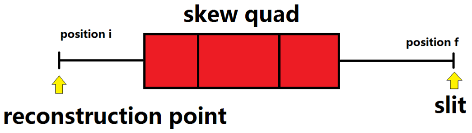


Figure 2: Schematic sketch of a skew quadrupole channel with a standard slit/grid emittance scanner used for the measurements.

At a first step it is assumed that the beam at the entrance of the beam line has no inter-plane correlations. Then the corresponding second-moments beam matrix C reads (in units of [mm] and [mrad]s)

$$C = \begin{bmatrix} 12.79 & 1.89 & 0 & 0 \\ 1.89 & 0.62 & 0 & 0 \\ 0 & 0 & 32.17 & 3.49 \\ 0 & 0 & 3.49 & 0.46 \end{bmatrix} \tag{10}$$

The skew quadrupoles were turned on (coupling lattice) and for six skew quadrupole settings the emittance measurements were repeated under preservation of full beam transmission. Using the assumed initial second-moments beam matrix mentioned above, i.e. neglecting the inter-plane correlations, the expected phase-space ellipses at the emittance measurement device can be calculated. To ease the calculation and to obtain more reliable results only one skew quadrupole was used at a time.

Comparing the calculated projected rms-ellipses to the measured ones, they do not fit if an initially uncorrelated beam corresponding to Eq. (10) is assumed. Accordingly, it is concluded that the initial beam inhabits inter-plane correlations, implying that the projected rms-emittances exceed the Eigen-emittances. A routine was developed to determine the initial coupling parameters. This method aims at determination of the initial second-moments beam matrix elements which fit best all measurements simultaneously. This numerical routine is described in [7]. The resulting second-moments beam matrix at the entrance of the beam line is (in units of [mm] and [mrad])

$$C = \begin{bmatrix} 12.79 & 1.89 & 0.18 & 0.40 \\ 1.89 & 0.62 & 01.75 & 0.29 \\ 0.18 & 1.75 & 32.17 & 3.49 \\ 0.40 & 0.29 & 3.49 & 0.46 \end{bmatrix} \tag{11}$$

Assuming this initial correlation the calculated and measured rms-ellipses agree very well. Therefore we assume that the inter-plane correlations have been determined correctly. Evaluation of the Eigen-emittances results in $\varepsilon_1 = 2.22(0.16)$ mm mrad and $\varepsilon_2 = 1.08(0.12)$ mm mrad. The corresponding coupling parameter is t=0.34(0.03). Due to the inter-plane correlations, the projected horizontal rms-emittance exceeds the lower of the Eigen-emittances by 68%. Removing the correlations by the skew triplet for instance would lower the horizontal emittance by 41%. This is equivalent to an increase of the horizontal brilliance, i.e. current to emittance ratio, by a factor of 1.68.

## ROSE DETECTOR

Instead of rotating the beam using a skew triplet one could also rotate the emittance scanner. Thus ROSE [8], a standard slit grid emittance scanner, using only one measuring plane which is rotatable around the beam axis has been developed. A technical drawing of the ROSE detector is shown in Fig. 3.

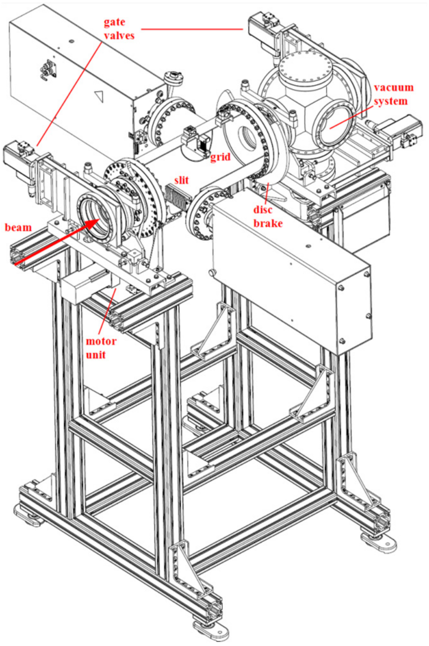


Figure 3: The ROSE detector system.

The two ports to house the slit and grid mechanics are on opposite sides of the rotating chamber to minimize the torque. The turbo molecular pump is mounted on a separate vacuum chamber that does not rotate. Two gate valves close the setup to easily separate ROSE from the accelerator vacuum for maintenance. The slit and grid geometry is shown in Fig. 4. The spatial resolution is given by the slit width of 0.2 mm, while the angular resolution is 3 (0.3) mrad (with up to 9 intermediate grid steps). Figure 5 shows the stepper motor used to rotate the chamber and an encoder to determine the rotation angle with a precision better than 0.5 degree. The disc brake is used to fix the chamber during the emittance measurement.

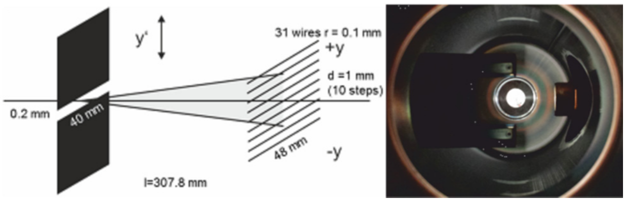


Figure 4: Schematic picture and photo of the slit and grid.

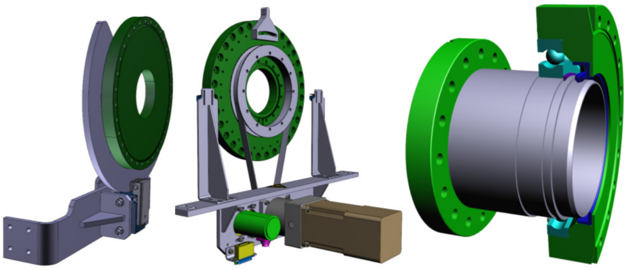


Figure 5: Technical drawing of the disc brake, motor unit and rotation flanges (left to right).

In combination with a magnetic doublet (see Fig. 6) it allows to determine the full 4d beam matrix C Eq. (1) in approximately one hour with a minimum of four emittance measurements at three different angles [9].

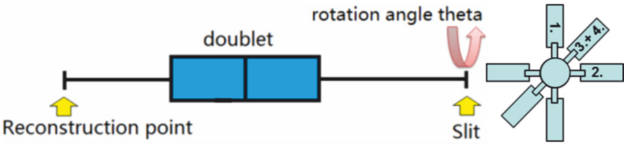


Figure 6: To obtain the beam matrix C at the reconstruction point all four emittance values are measured using ROSE behind a magnetic doublet.

As shown in Figure 6 the emittance measurements are done using a magnetic setting a for the 0°, 45°, and 90° measurement and another magnet setting b for the 45° measurement. A minimum of four measurements is sufficient to measure the complete four-dimensional second-moments beam matrix.

1. 0° doublet setting a
2. 90° doublet setting a
3. + 4. 45° doublet setting a and b

This method to measure the full 4d beam matrix using ROSE is described in detail in [9].

At first the hardware, the control system, and the evaluation software have been tested without beam. Yet commissioning of the vacuum system was of main concern as rotary shaft seals have been used instead of commercially available rotation flanges with differential pumping stages. In a first attempt dry seals have been used. But already after some tens of rotations a strong degradation effect on the seals, as visible in Fig. 7, has been observed. Thus the surface of the rotary shaft has been polished and vacuum grease is now used to minimize friction and prevent dust from getting between the surfaces.

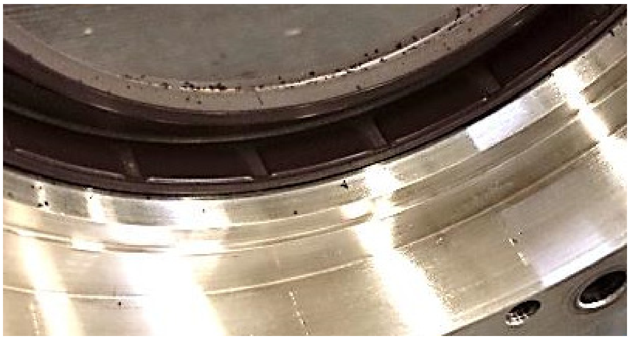


Figure 7: Damaged seal after some tens of dry turns.

A stationary pressure of $5 \cdot 10^{-8}$ mbar and $1 \cdot 10^{-7}$ mbar during rotation is now routinely reached and no degradation effect has been observed since then.

## COMMISSIONG RESULTS

Beams of 1.4 MeV/u $^{40}Ar^{9+}$ and $^{83}Kr^{13+}$ from the high charge state injector HLI at GSI served to commission the hard- and software of ROSE, to benchmark it against existing emittance scanners, and to proof its capability to measure the 4d beam matrix. To achieve this, an emittance scanner park shown in Fig. 8 has been used.

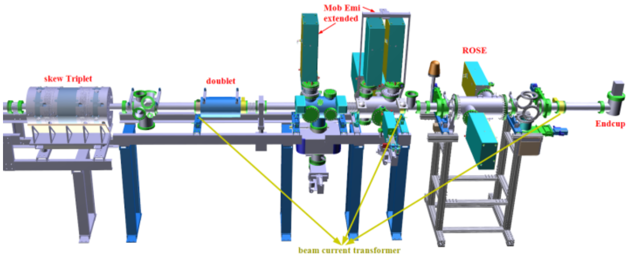
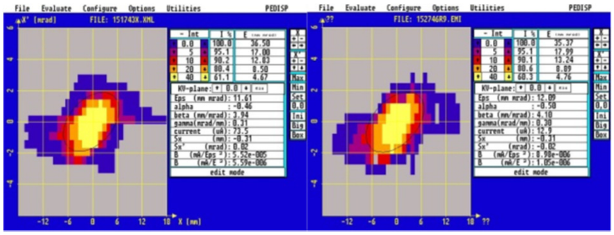


Figure 8: Experimental beamline behind the HLI at GSI used for the commissioning of ROSE.

It comprises a skew triplet to enforce and modify the coupling, a doublet to achieve the different magnetic settings that are required for the measurement, an existing standard high resolution emittance scanners called MobEmi, and ROSE. Throughout the beamline three current transformers and one end cup are used to measure and ensure full beam transmission.

To first benchmark ROSE the emittance of a 1.4 MeV/u $^{40}Ar^{9+}$ beam from the HLI ECR source has been measured horizontally using the well calibrated emittance scanner MobEmi and ROSE at 90°. To compare the results the emittance measured with MobEmi has been propagated to the ROSE slits shown in Fig. 9. In a second step the horizontal and vertical emittances have been measured with both scanners for different quadrupole duplet settings *a* and *b*. The comparison at the entrance of the quadrupole doublet is shown in Fig. 10. The measured emittances at 0° (vertical) and 90° (horizontal) are in good agreement for all three emittance scanner set-ups. ROSE has been successfully benchmarked against the MobEmi emittance scanner.



FILE: 151743X.XML

| - Int | I % | E (mm mrad) |
|---|---|---|
| 0.0 | 100.0 | 36.50 |
| 5 | 95.1 | 17.00 |
| 10 | 90.2 | 12.83 |
| 20 | 80.4 | 8.50 |
| 40 | 61.1 | 4.67 |

KV-plane: 0.0
Eps (mm mrad): 11.61
alpha : -0.46
beta (mm/mrad): 3.94
gamma(mrad/mm): 0.31
current (uA): 73.5
Sx (mm): -0.31
Sx' (mrad): 0.02
B (mA/Eps ²): 5.52e-005
B (mA/E ²): 5.59e-006

FILE: 15274GR9.EMI

| - Int | I % | E (mm mrad) |
|---|---|---|
| 0.0 | 100.0 | 35.37 |
| 5 | 95.1 | 17.99 |
| 10 | 90.1 | 13.24 |
| 20 | 80.6 | 8.09 |
| 40 | 60.3 | 4.76 |

KV-plane: 0.0
Eps (mm mrad): 12.09
alpha : -0.50
beta (mm/mrad): 4.10
gamma(mrad/mm): 0.30
current (uA): 12.9
Sx (mm): -0.31
Sx' (mrad): -0.02
B (mA/Eps ²): 8.98e-006
B (mA/E ²): 1.05e-006

Figure 9: Comparison of the measured emittances using MobEmi (left) and ROSE (right).

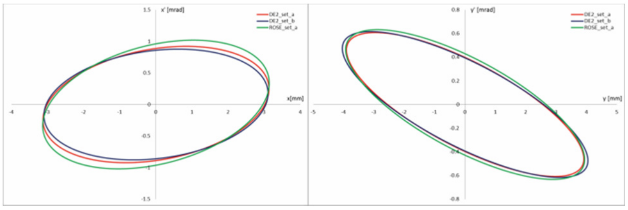


Figure 10: The beam emittance at the quadrupole duplet entrance, determined for different magnetic fields of the quadrupole duplet using ROSE and MobEmi.

To experimentally proof ROSE's capability to measure the 4d transverse beam matrix the inter plane correlations of the HLI of a 1.4 MeV/u $^{83}$Kr$^{13+}$ beam have been measured. As no significant initial correlations were found to be present, controlled coupling of the planes by using the skew triplet has been enforced. Figure 11 shows the measured coupling moments and in Fig. 12 they are compared to the uncorrelated beam. For both skew quadrupole settings a full emittance scan using ROSE has been performed. As the beam parameters transformed back to the entrance of the skew triplet shown on the bottom of the plot match very well, the reliability of the ROSE measurements is experimentally proven. The expected effect of the skew triplet has been confirmed with ROSE. Figure 13 shows the obtained Eigen-emittances of the HLI Krypton beam. Applying error analysis, the obtained Eigen-emittances are: $\varepsilon_1 = 2.43$ (0.19) mm mrad and $\varepsilon_2 = 2.04$ (0.17) [mm mrad] with a coupling parameter $t = 0.94$ (0.21) and the beam matrix C is given in.

$$C = \begin{bmatrix} 8.57 & -4.34 & -3.28 & -1.10 \\ -4.34 & 3.35 & -0.74 & 1.52 \\ -3.28 & -0.74 & 11.20 & -3.05 \\ -1.10 & 1.52 & -3.05 & 1.87 \end{bmatrix} \quad (12)$$

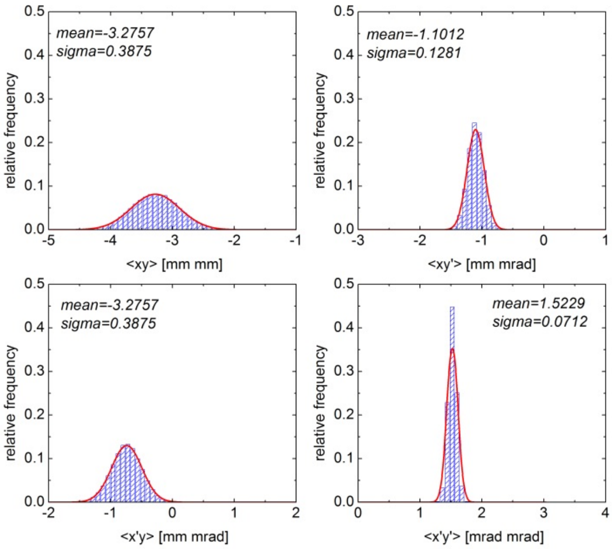


Figure 11: Each measured moment entering into the evaluation was varied randomly following a Gaussian distribution centered on its measured value.

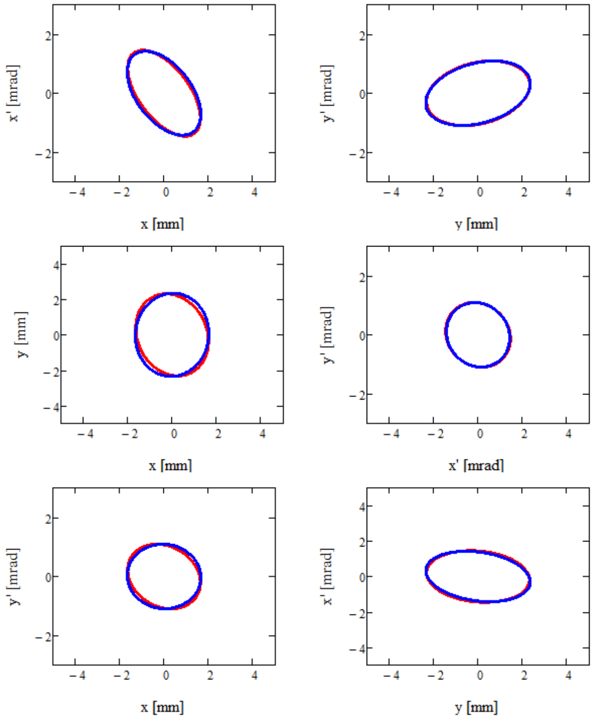


Figure 12: Rose measurements shown in Fig. 14 transformed back to the entrance of the skew triplet.

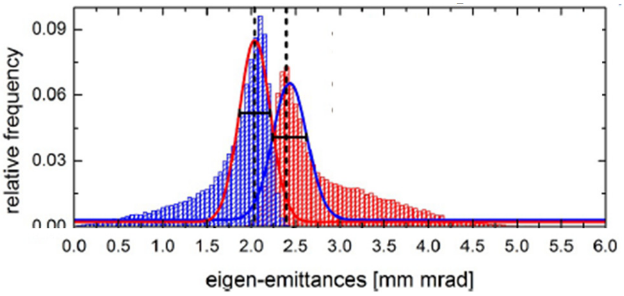


Figure 13: From the measured moments derived Eigen-emittances of the HLI 1.4 MeV/u $^{83}$Kr$^{13+}$ beam.

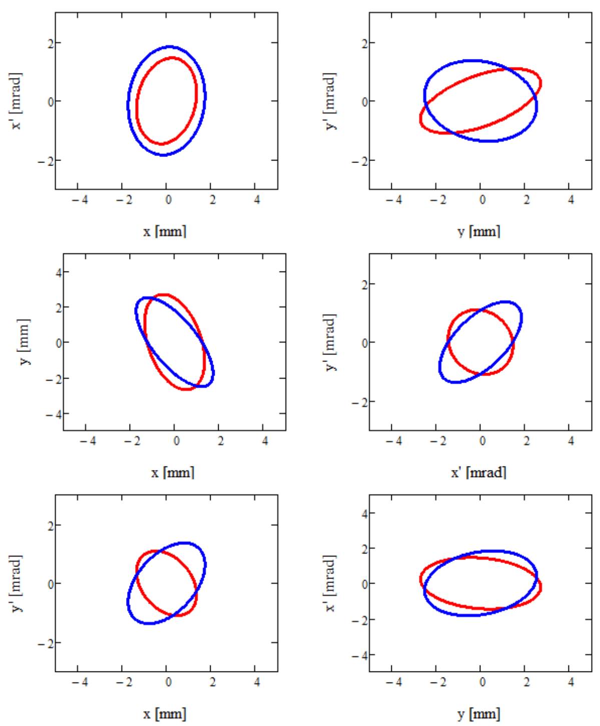


Figure 14: Rose measurements of a 1.4 MeV/u $^{83}$Kr$^{13+}$ for two different skew triplet settings (red off, blue on).

After commissioning in the HLI beam line, ROSE has been set up in the transfer channel beamline that has been used for the skew quadrupole variation measurement. Because of FAIR related RF upgrades the $^{238}$U$^{28+}$ beam energy in the transfer channel towards SIS18 was limited to 5.9 MeV/u. Figure 15 and Eq. (13) show the successful measurement of 4d beam matrix using ROSE. Comparing the normalized transverse emittance and the Eigen-emittance listed in Table 1 the results of the skew and ROSE method do compare quite well.

$$C = \begin{bmatrix} 5.99 & -0.62 & -1.15 & 0.25 \\ -0.62 & 0.68 & 0.36 & 0.20 \\ -1.15 & 0.36 & 7.60 & -1.04 \\ 0.12 & 0.20 & -1.04 & 0.41 \end{bmatrix} \tag{13}$$

Table 1 Measured 4d 2nd Moments Matrix of $^{238}$U$^{28+}$ Beams in the Transfer Channel in Units of [mm], [mrad]

| | Skew | ROSE |
|---|---|---|
| $\varepsilon_x$ | 2.1 | 1.94 (0.05) |
| $\varepsilon_y$ | 1.62 | 1.42 (0.04) |
| $\varepsilon_1$ | 2.22 (0.16) | 2.07 (0.07) |
| $\varepsilon_2$ | 1.08 (0.12) | 1.07 (0.06) |
| t | 0.34 (0.03) | 0.33 (0.05) |

The attempt to remove the measured coupling t=0.33 using the skew triplet did not succeed. Later during off-line analysis we found a bug in the software calculating the decoupling section.

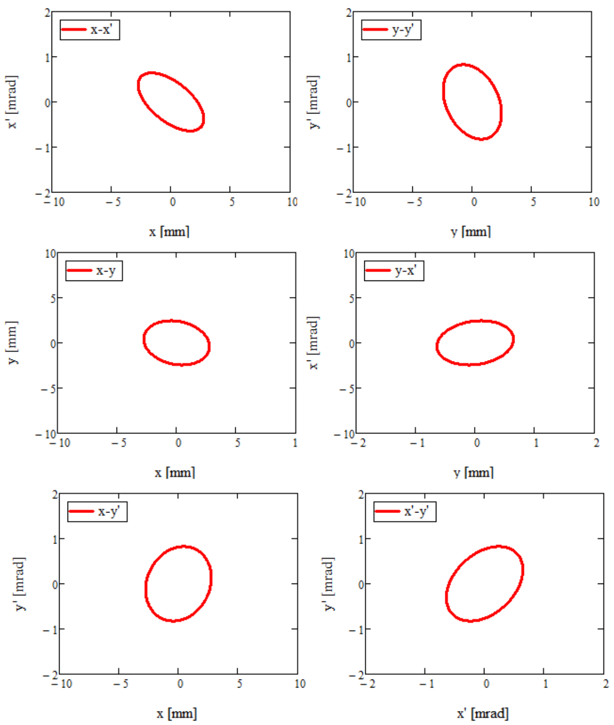


Figure 15: Measured 4d beam matrix using ROSE for a $^{238}$U$^{28+}$ at 5.9 MeV/u in the transfer channel before SIS18.

## CONCLUSION & OUTLOOK

ROSE has been commissioned successfully. To our knowledge this is the only device that can measure full 4d ion beam parameters at kinetic energies above 150 keV/u. With **NTG** Neue Technologien GmbH & Co. KG we have found an industrial partner, and together we are planning to develop a turnkey 4d emittance scanner device for the accelerator community.

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