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ROSE - A ROTATING 4D EMITTANCE SCANNER

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Abstract

The detector system ROSE [1, 2], allowing to perform 4D emittance measurements on heavy ion beams independent of their energy and time structure, has been built and successfully commissioned in 2016 at GSI in Darmstadt, Germany. This method to measure the four dimensional emittance has then been granted a patent in 2017. The inventors together with the technology transfer department of GSI have found an industrial partner to modify ROSE into a fully standalone, mobile emittance scanner system. This is a three step process involving the ROSE hardware, the electronics ROBOMAT* and the software working packages. The electronics was commissioned at the ECR test bench of the Heidelberg ion therapy facility HIT in June 2019. Currently our main focus is on the development of the 4D software package FOUROSE**. This contribution presents the actual status and introduces the multiple possibilities of this 4D emittance scanner.

MOTIVATION

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, tilted magnets or just simply by beam losses. An example for matching the round transverse phase space of a linac beam to the flat acceptance of a synchrotron is shown in Figure 2. To accomplish this, inter-plane correlations are a prerequisite [3, 4].

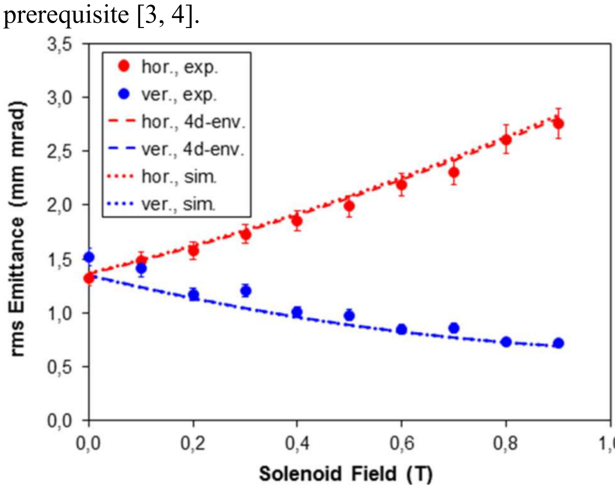

Figure 1: One knob emittance transfer using EMTEX [3].

In order to remove correlations that do increase the projected rms-emittances they must be quantified by measurements. This applies especially if space charge effects are involved as they cannot be calculated analytically.

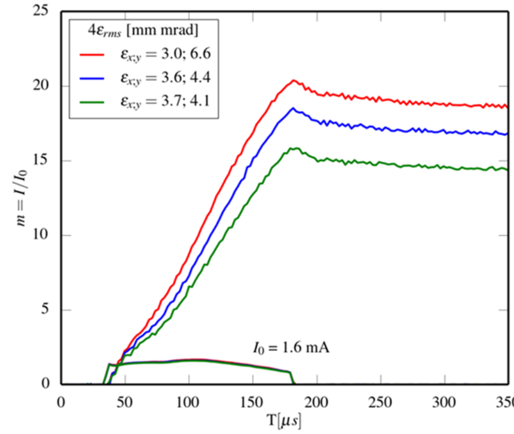

Figure 2: The emittance transfer using EMTEX directly translates in increased injection efficiency into SIS18 [4].

Using the skew triplet of the EMTEX setup we have measured the increase of the projected rms-emittance of a U28+ beam with 11.4 MeV/u to be in the order of 75%. Removing this inter-plane coupling could increase the beam brilliance and thus the injection efficiency into SIS18 [5].

THEORY OF ROSE

ROSE is a standard slit-grid emittance scanner using only one measuring plane which is rotatable around the beam axis. In combination with a magnetic doublet it allows to determine the full 4D beam matrix C with a minimum of four emittance measurements at three different angles.

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

Figure 3 shows that the emittance measurements are done using a quadrupole doublet setting (a) for the 0°, 45°, and 90° measurement and a setting (b) for another 45° measurement.

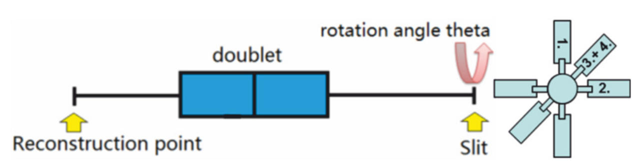

Figure 3: To obtain the beam matrix C at the reconstruction point four emittance measurements are done using ROSE behind a quadrupole doublet.

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Four measurements are 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 and the mathematics behind ROSE is described in detail in [2].

DETECTOR SYSTEM ROSE

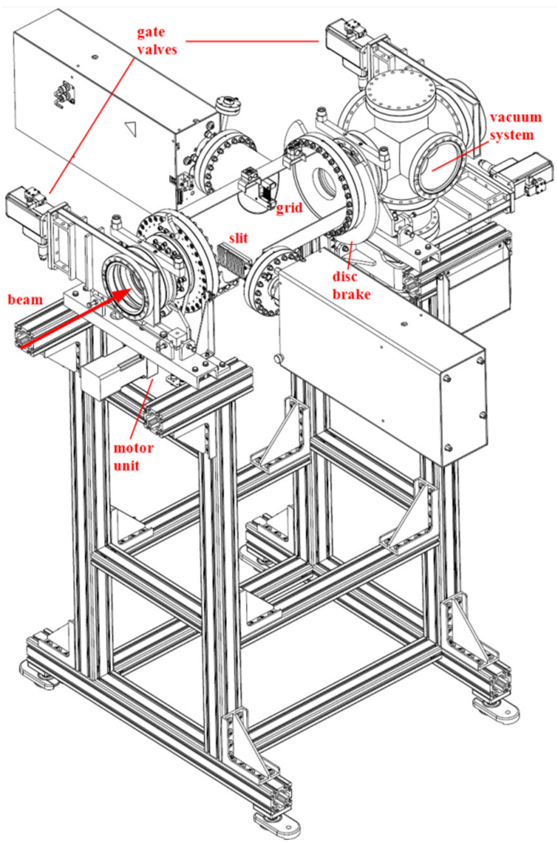

Figure 4: The ROSE detector system. The rotatable slit-grid vacuum vessel and the separate pumping chamber are installed between two gate valves to protect the accelerator vacuum during rotation. The disc brake system avoids vibration of the vessel during the measurement.

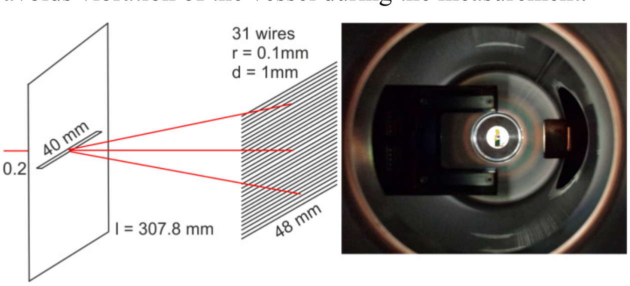

Figure 5: Schematic picture and photo of the slit and grid.

Figure 4 shows a technical drawing of the ROSE detector. The two ports housing 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 separate ROSE from the accelerator vacuum during rotation and for maintenance. The stepper motor used to rotate the chamber allows for a precision better than half a degree and the disc brake is used to stabilize the chamber during the emittance measurement. Figure 5 shows a detailed view of the slit and grid geometry inside the ROSE vessel. The spatial resolution is given by the slit width of 0.2 mm, while the angular resolution is 3 mrad. If necessary the angular resolution may be increased to 0.3 mrad by using up to 9 intermediate grid steps, yet this lengthens the measurement by the same order of magnitude.

BEAM COMMISSIONING OF ROSE

Beams of 1.4 MeV/u $^{40}Ar^{9+}$ and $^{136}Xe^{19+}$ 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. Figure 6 shows a schematic view of the beamline and emittance scanner setup to achieve this. It comprises a skew triplet to enforce and modify the coupling, a doublet to achieve the different quadrupole settings that are required for the measurement, an existing standard high resolution emittance scanners called Mob-Emi, and ROSE. Throughout the beamline three current transformers and one end cup are used to measure and to ensure full beam transmission. The horizontal and vertical emittances of the $^{40}Ar^{9+}$ beam have been measured with both scanners for different quadrupole doublet settings (a) and (b) and the compared emittances at the entrance of the quadrupole doublet have been in very good agreement.

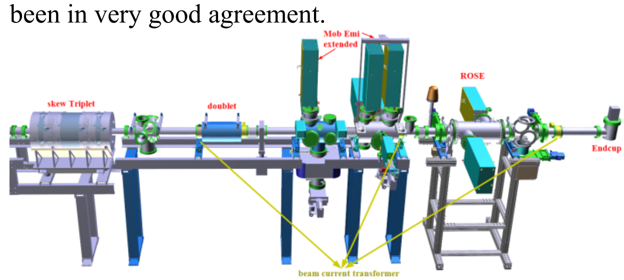

Figure 6: Schematic view of the experimental setup used for the commissioning of the ROSE detector and its capability to measure the full 4D beam matrix.

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 Ar^{9+} 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 7 shows the measured coupling moments and in Figure 8 they are compared to the uncorrelated beam at the entrance of the skew triplet. 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 match very well, the reliability of the ROSE 4D measurements is experimentally proven. The expected effect of the skew triplet has been confirmed with ROSE. Figure 9 shows the obtained eigen-emittances [6] of the HLI Argon beam. Applying error analysis, the obtained

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eigen-emittances are: ε_1 = 2.43 (0.19) mm mrad and ε_2 = 2.04 (0.17) mm mrad and the corresponding beam matrix C is given in mm mrad:

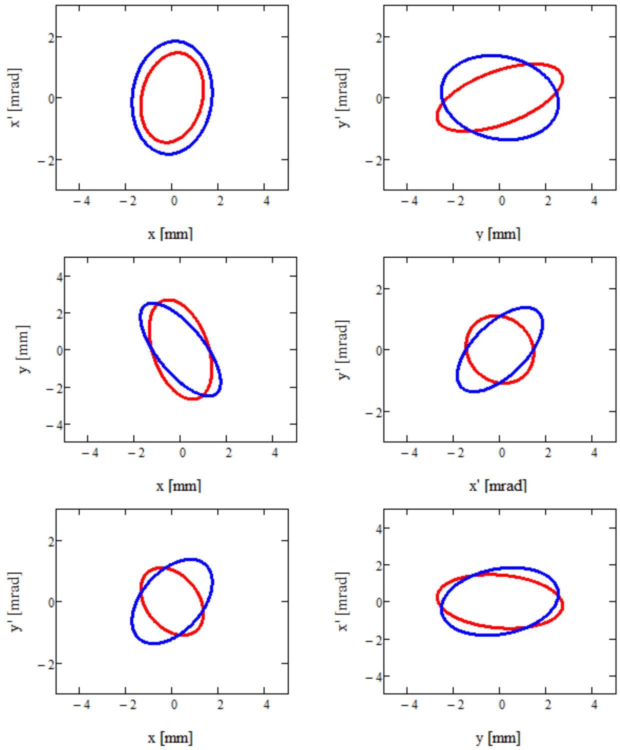

Figure 7: ROSE measurements of a 1.4 MeV/u Ar^{9+} for two different skew triplet settings (red off, blue on).

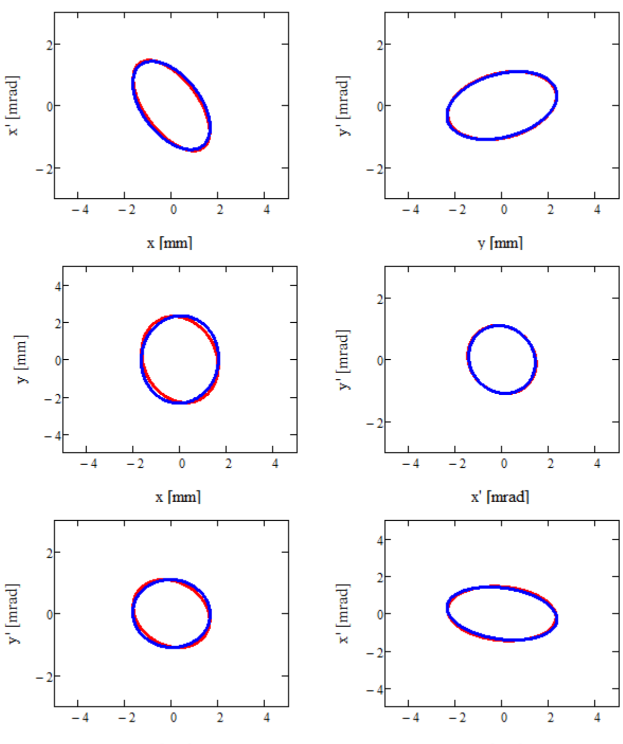

Figure 8: ROSE measurements shown in Figure 7 transformed back to the entrance of the skew triplet.

$$C = \begin{bmatrix} 8.57 & -4.34 & -3.28 & -1.10 \\ -4.34 & 3.35 & -0.74 & 1.52 \\ -3.28 & -0.74 & 11.20 & -3.05 \\ -1.10 & 1.52 & -3.05 & 1.87 \end{bmatrix} \quad (2)$$

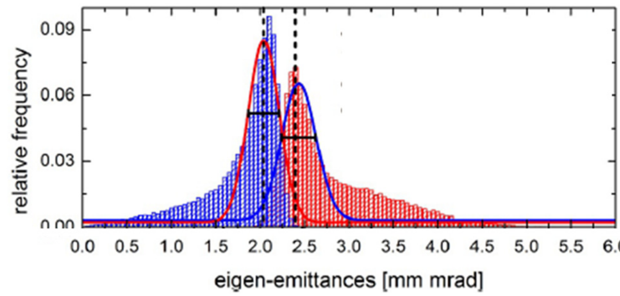

Figure 9: The two eigen-emittances being derived from the measurement of the HLI 1.4 MeV/u Ar^{9+} beam.

ELECTRONICS – ROBOMAT

For the commissioning of the prototype of ROSE the GSI control system has been used. However, ROSE as a fully standalone mobile emittance scanner has to be independent of a specific control system. Thus ROBOMAT [7] was specified to control the ROSE movements, measuring and saving the data. ROBOMAT itself has no special 4D feature and is standard emittance scanner electronics with the additional degree of freedom to rotate the scanner freely around the beam axis. It comprises a housing rack, an integrated PC, on which all the software for controlling the devices, data taking and handling as well as monitoring the interlock status is installed.

Figure 10: ROSE (left) and ROBOMAT (right) as delivered by NTG at the HIT facility for the commissioning with beam.

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For measuring the grid currents, electronics by Pyramid F3200E has been chosen, as it fulfills all requirements in accuracy, speed, and number of channels. All the technical details and requirements have been specified by the GSI post Stripper Upgrade department and discussed with NTG. This resulted in a list of key features backing the offer of NTG. Figure 10 shows ROSE together with the finished ROBOMAT as it has been delivered for beam commissioning and the site acceptance test at the **H**eidelberger **I**onenstrahl-**T**herapiezentrum HIT [8].

BEAM COMMISSIONING OF ROBOMAT

For commissioning of the ROBOMAT we have been allowed to use the ECR ion source test bench of HIT. Figure 11 shows the setup of the beamline. H_3^+ ions from the ECR source have been used in dc and pulsed mode.

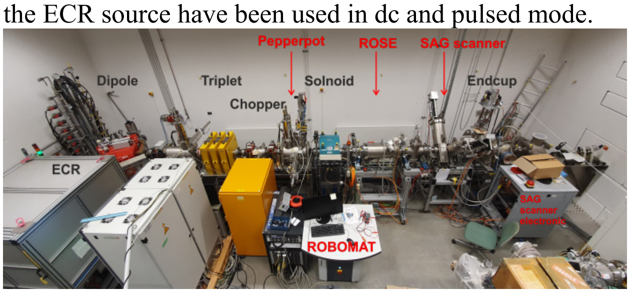

Figure 11: The setup for beam commissioning and the site acceptance test at the HIT facility

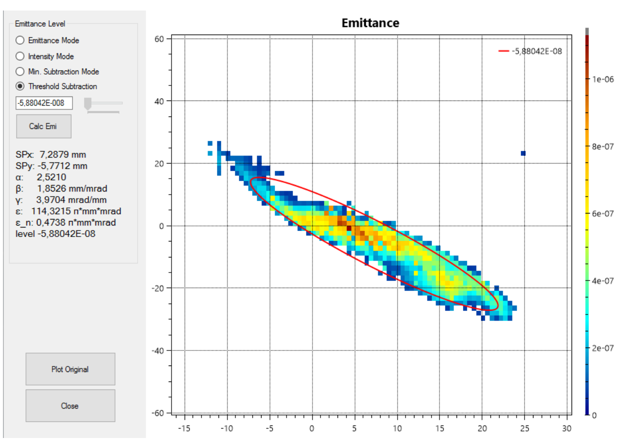

Figure 12: Example of a measured and evaluated horizontal beam emittance using the ROBOMAT electronics at the HIT facility.

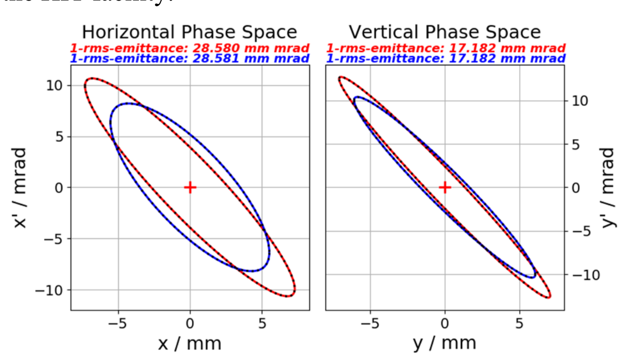

Figure 13: Comparison of the horizontal and vertical emittance using the ROSE (red) and SAG (blue) emittance scanner (by courtesy of R. Cee, HIT).

The beamline behind the dipole for charge separation of the ECR beam comprises a triplet, a chopper for pulsed beam operation, and a solenoid for matching the beam downstream. Behind the solenoid ROSE followed by the emittance scanner SAG and an end cup have been installed. Along the beamline we used beam current transformers and Faraday cups to ensure full transmission and SEM grids for beam tuning. Figure 12 shows the evaluated emittance using the ROBOMAT electronics and in Fig. 13 the results of both emittance scanners have been compared. All other specified features of the ROBOMAT have been successfully tested and confirmed as well.

SOFTWARE – FOUROSE

The software FOUROSE will provide the user with a tool to plan, perform, and evaluate 4D emittance measurements. As for the development of ROBOMAT the software development is also third party funded, this time within the LOEWE 3 state funding [9]. The software shall guide the user through the process of a 4D emittance scan on a configurable beam line, consisting of regular and skew quadrupoles, drifts and the emittance scanner. The user defines the beamline and maximum quadrupole field strength available. Then with all magnets off, the measured horizontal and vertical projection of the beam emittance will be used by the software to calculate the optimum settings for the 4D emittance scan and will guide the user through the measurement procedure. Once all required emittance scans are performed, the software will generate an evaluation report. In case a skew triplet is available the software may suggest magnet settings for the skew triplet to reduce the inter-plane coupling to increase the beam brilliance. The software development has started with the approval of funding in May 2019 and therefore is still at the beginning.

CONCLUSION

We have invented, build and successfully commissioned a 4D-emittance scanner for heavy ion beams independent of their kinetic energy and time structure. Together with an industrial partner we have developed and commissioned a fully standalone, mobile emittance scanner. The final part of this project has started this year and we expect to have the 4D software, as part of a configurable, mobile emittance scanner, ready in spring 2021.

ACKNOWLEDGEMENTS

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REFERENCES

[1] "Drehmodul für eine Beschleunigeranlage", Deutsche Patentanmeldung Nr. 102015118017.0 eingereicht am 22.10.2015 beim Deutschen Patent- und Markenamt.

[2] C. Xiao, M. Maier, X. N. Du, P. Gerhard, L. Groening, S. Mickat, and H. Vormann, Rotating system for four-dimensional transverse rms-emittance measurements: *Phys. Rev. Accel. Beams* 19, 072802 – Published 19 July 2016.

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

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

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

[6] A. J. Dragt, General moment invariants for linear Hamiltoniansystems, *Phys. Rev. A* 45, 2572 (1992).

[7] gefördert durch: Bundesministerium für Wirtschaft und Energie.

[8] T. W. Winkelmann *et al.*, "Status Report at the Heidelberg Ion-Beam Therapy (HIT) Ion Sources and the Testbench", in *Proc. 21st Int. Workshop on ECR Ion Sources (ECRIS'14)*, Nizhny Novgorod, Russia, Aug. 2014, paper MOPPH004, pp. 49-51.

[9] Dieses Projekt (HA-Projekt-Nr.: 694_19-14) wird im Rahmen der Innovationsförderung Hessen aus Mitteln der LOEWE – Landes-Offensive zur Entwicklung Wissenschaftlichökonomischer Exzellenz, Förderlinie 3: KMUVerbundvorhaben gefördert. frank.schmidt-foehre@desy