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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 standalone, commercially available emittance scanner system. This is a three step process involving the hardware, the electronics and the software working packages. It is planned to have a configurable customer product ready by end of 2020. This contribution presents the actual status and introduces the multiple possibilities of this 4D emittance scanner.

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, tilted magnets or just simply by beam losses. Figure 1 shows the simulation of a coupled and an uncoupled beam with initially identical projected horizontal and vertical rms-emittances through a solenoid channel. This illustrates the fact that initial coupling influences the final horizontal and vertical beam size.

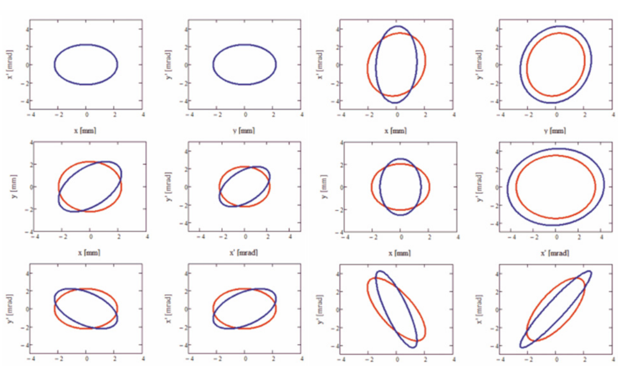

Figure 1: Simulation of an initially uncoupled (red) and coupled (blue) ion beam (left) at the exit of a solenoid channel (right).

For some applications, as for example matching the round transverse phase space of a linac beam Fig. 2 to the flat acceptance of a synchrotron [3], [4], inter-plane correlations are a prerequisite Fig. 3.

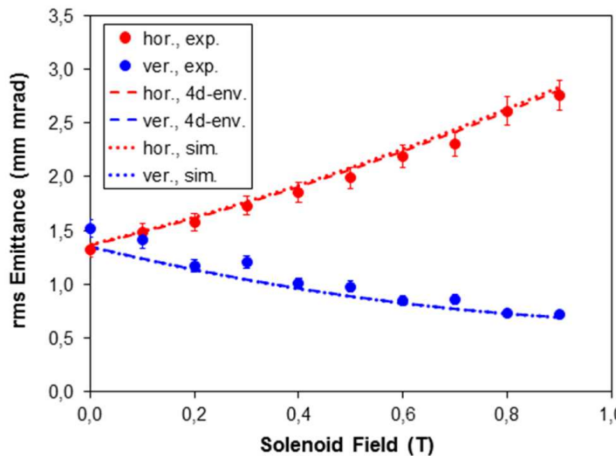

Figure 2: One knob emittance transfer using EMTEX [3].

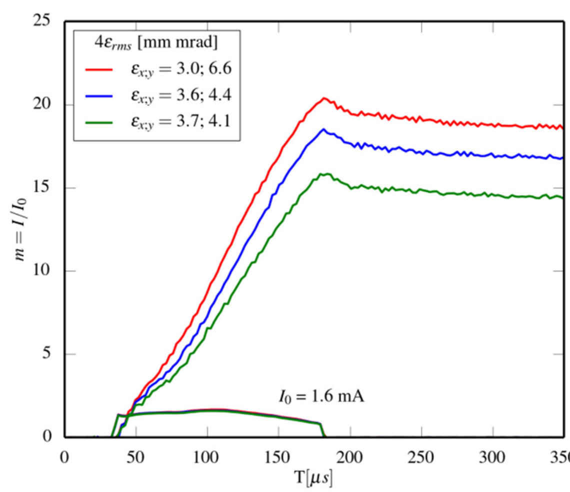

Figure 3: The emittance transfer using EMTEX directly translates in increased injection efficiency into SIS18 [4].

In order to remove correlations that do increase the projected rms-emittance, they must be quantified by measurements. This applies especially if space charge effects are involved as they cannot be calculated analytically. Using the skew triplet of the EMTEX setup we have measured the increase of the projected rms-emittance of a U^{28+} 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 by 75% [5].

There is considerable work on measuring four-dimensional distributions using pepper-pots [6] - [9] for electron beams or ion beams at energies below 150 keV/u, for which the beam is fully stopped by the pepper-pot mask. However, due to technical reasons this method is not

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applicable at energies above 150 keV/u, i.e., doubtful readout by temperature-dependent screens and fixed resolutions by holes and screens [10].

In the following we report about ROSE, an alternative method to measure the full 4D beam matrix that has been successfully commissioned and is currently modified to become a customer product in industry. This involves three working packages concerning the hard- and software and a stand-alone electronics to become independent of a specific accelerator control system.

ROSE PRINCIPLE

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 (see Eq. 1) in approximately one hour with a minimum of four emittance measurements at three different angles.

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

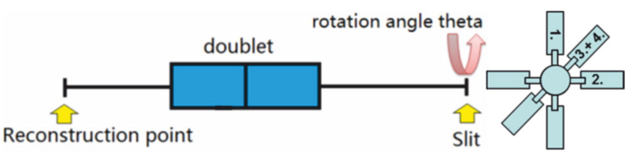

Figure 4: To obtain the beam matrix C at the reconstruction point four emittance values are measured using ROSE behind a magnetic doublet.

As shown in Figure 4 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. 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)

The method and mathematics of ROSE is described in detail in [2].

DETECTOR SYSTEM – ROSE

A technical drawing of the ROSE detector is shown in Figure 5. 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 are to separate ROSE from the accelerator vacuum during rotation and for maintenance. The slit and grid geometry is shown in Figure 6. 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 time. The stepper motor used to rotate the chamber and an encoder to determine the rotation angle allow for a precision better than half a degree. The disc brake is used to stabilize the chamber during the emittance measurement.

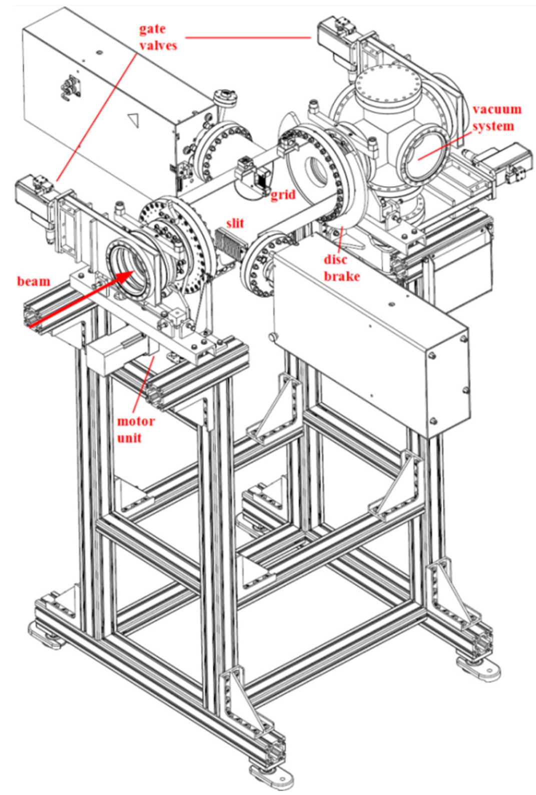

Figure 5: The ROSE detector system. The rotatable slit-grid vacuum vessel and the separate pumping chamber are installed between two gate valves to protect the accelerator vacuum during rotation. To avoid vibration during the measurement a disc brake system clutches the chamber.

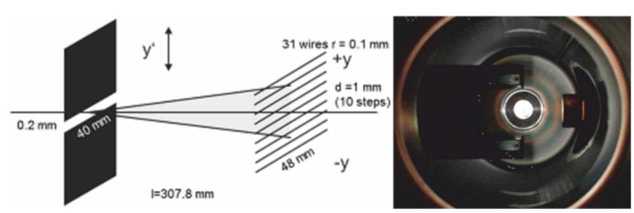

Figure 6: Schematic picture and photo of the slit and grid.

COMMISSIONG RESULTS

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. To achieve this, an emittance scanner park shown in Figure 7 has been used.

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 Mob-Emi, and ROSE. Throughout the beamline three current transformers and one end cup are used to measure and to ensure full beam transmission.

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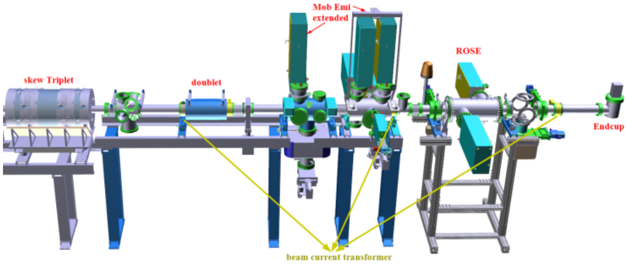

Figure 7: Experimental setup used for commissioning.

To first benchmark ROSE the emittance of a 1.4 MeV/u 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. 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 Figure 8. 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.

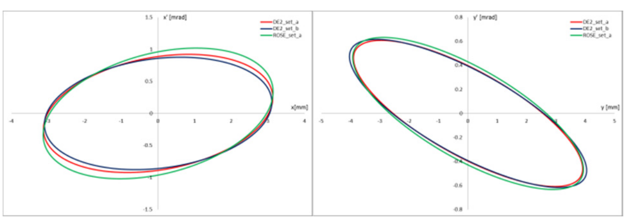

Figure 8: The beam emittance at the quadrupole duplet entrance, determined for different magnetic fields of the quadrupole duplet using ROSE and MobEmi.

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 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 9 shows the measured coupling moments and in Fig. 10 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 shown in Fig. 11 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 12 shows the obtained eigen-emittances [11] of the HLI Argon beam. Applying error analysis, the obtained 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 Eq. 2 in mm mrad.

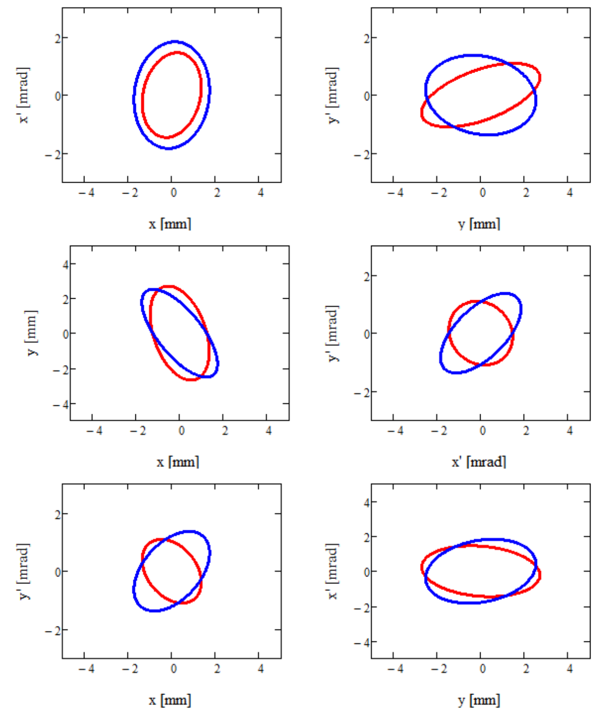

Figure 9: ROSE measurements of a 1.4 MeV/u Ar^{9+} for two different skew triplet settings (red off, blue on).

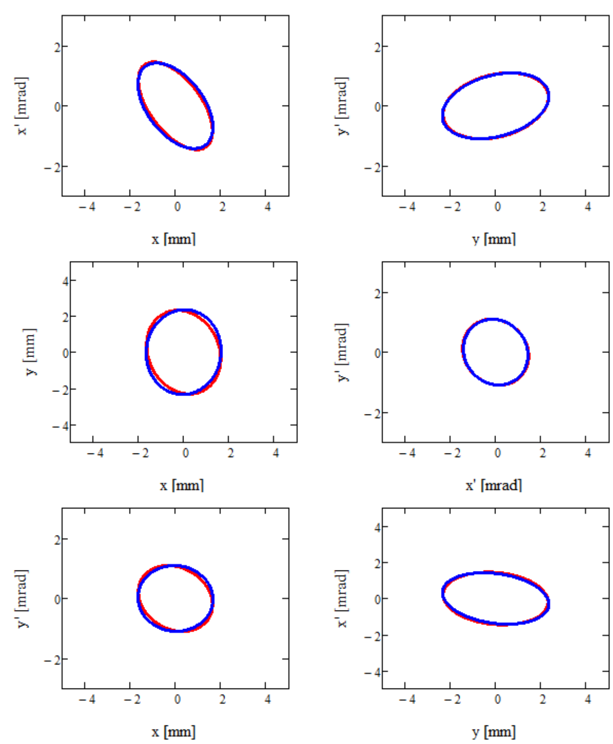

Figure 10: ROSE measurements sown in Fig. 9 transformed back to the entrance of the skew triplet.

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

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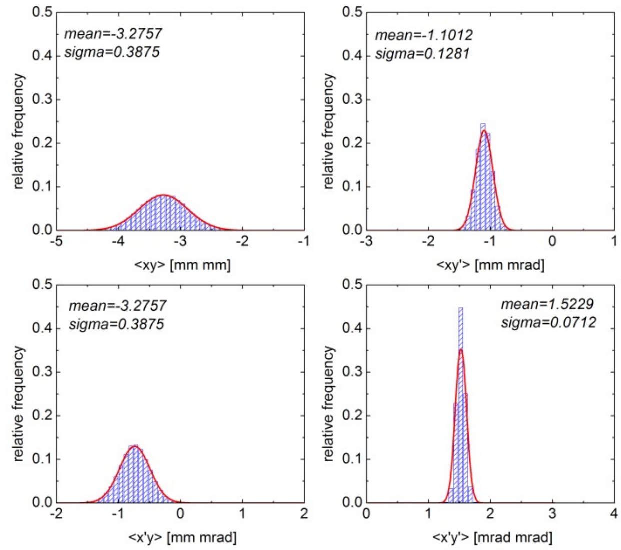

Figure 11: Measured moments with the skew triplet switched on.

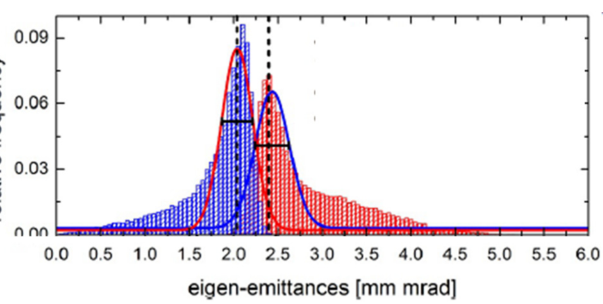

Figure 12: The two eigen-emittances being derived from the measurement of the HLI 1.4 MeV/u Ar^{9+} beam.

ELECTRONICS – ROBOMAT

For the commissioning of the prototype of ROSE the GSI control system has been used. However, ROSE as a mobile emittance scanner has to be independent of a specific control system. Thus ROBOMAT [12] was specified as standalone emittance electronics, independent of an accelerator control system to control the ROSE movements, measuring and saving the data as well as monitoring the ion beam current and vacuum conditions in the vessel. ROBOMAT itself has no special 4D feature and is a 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 Beckhoff industrial PC, on which all the software for controlling the devices, data taking and handling as well as monitoring the interlock status is installed. As the cable length for the grid electronics is limited the user may connect to it via Ethernet. For data taking of the grid currents electronics by Pyramid F3200E has been chosen as it fulfills all requirements in accuracy, speed, and number of channels. It has arrived at NTG as shown in Fig. 13 and is currently prepared, tested and commissioned at NTG.

The three stepper motors and their controllers for moving the emittance slit, grid, and the rotation of the vessel have arrived as well and are shown in Fig. 14.

Figure 13: The grid electronics Pyramid F3200E that will be used has arrived at NTG and is currently prepared, tested and commissioned.

Figure 14: The stepper motor and associated controller units have arrived at NTG and will be integrated into ROSE to replace the GSI systems.

Because of economic and practical reasons NTG has decided to exchange the analog stepper motors of the existing prototype ROSE by a more modern digital type shown in Figure 14. These components have as well already arrived and should be integrated into ROSE by the end of October 2018. The technical details and requirements have been discussed with NTG and the colleges of the GSI beam diagnostics- and the Linac department. This resulted in a list of key features backing the offer of NTG. The key features of ROBOMAT and the different measurement modes are given in the following list.

ROBOMAT is:

- controlling all movements of ROSE,
- performing the emittance measurements,
- capable to measure DC and pulsed beam,
- covering beam currents ranging 10µA - 100mA,
- including ion current measurement,
- storing emittance data in XML format,
- visualizing the emittance measurements,
- handling the multiple internal and external interlock signals e.g.:
  - beam on
  - moving device
  - vessel vacuum pressure
  - slit water cooling
  - gate valve status

The possible measurement modes are:

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- **Parallel**: slit and grid are moving in parallel.
- **Angular offset**: slit and grid constant offset.
- **Diagonal**: slit-grid offset as function of position.
- **Intermediate step**: fine extra grid steps to increase the angular resolution.
- **Double grid**: two grid positions to double the grid area
- **Ultrafast**: drive by measurement while moving.
- **Profile grid**: only the grid is in the beam.
- **Background**: measurement without beam.

SOFTWARE – ROSOFT

The software ROSOFT will provide the user with a tool to plan, perform, and evaluate 4D emittance measurements. It is going to be included into the base 2D functionality of ROBOMAT. It is supposed to perform the following actions sketched in Fig. 15 on a user configurable beam line, consisting of regular and skew quadrupoles, drifts and the emittance scanner. The user defines the beamline and maximum magnetic 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 optimum settings for the 4d emittance scan which will guide the user through the measurement procedure. Once all required four 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.

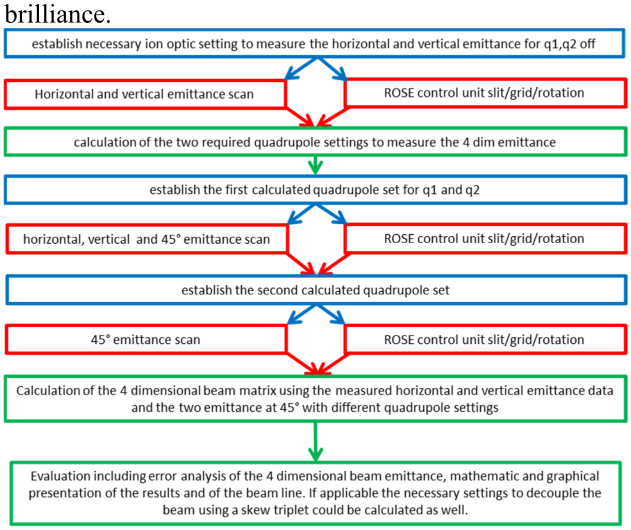

Figure 15: software flowchart: necessary actions within the external accelerator control system in blue, in red ROBOMAT functions and in green the ROSE software interaction.

TIMELINE

As we have a working prototype the next big step is the commissioning of the standalone electronics ROBOMAT which is scheduled for beginning of 2019. To develop a Software package with the full 4d capability will take approximately 2 years. NTG has applied for a third party funding which may be provided by the state of Hessen we are waiting right now for the positive decision before we can start in this matter. In those two years in parallel to the software programming NTG may improve the hardware of ROSE for example by switching to a 2 chamber system. So we expect to be able to deliver our first customer product end of 2020.

CONCLUSION

We have invented, build and successfully commissioned a 4d-emittance scanner for heavy ion beams independent of their kinetic energy and time structure. We have found an industrial partner and together we are developing a turnkey 4d emittance scanner for the accelerator community. The project has started this year and we expect to have a configurable customer product ready in the end of 2020.

ACKNOWLEDGEMENTS

My special gratitude goes to all GSI staff involved in this project. This includes the technical infrastructure as well as the support in the mathematics and physics tasks. The technology transfer department has been very successful in raising funds and finding an industrial partner. Of course I'd like to thank the company NTG for their interest to realize this project together with us. And we would like to thank the Bundesministerium für Wirtschaft und Energie for the possibility to get third party funding for the development of ROBOMAT.

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