A CORRECTION SCHEME FOR THE HEXAPOLAR ERROR OF AN ION BEAM EXTRACTED FROM AN ECRIS

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Abstract

The extraction of any ion beam from ECRIS is determined by the good confinement of such ion sources. It has been shown earlier, that the ions are coming from these places, where the confinement is weakest. The assumption that the low energy ions are strongly bound to the magnetic field lines require furthermore, that only these ions starting on a magnetic field line going through the extraction aperture can be extracted. Depending on the setting of the magnetic field, these field lines may come from the loss lines at plasma chamber radius. Because the longitudinal position of these field lines depends on the azimuthal position at the extraction electrode, the ions are extracted from different magnetic flux densities. Whereas the solenoidal component can only be transferred into another phase space projection, the hexapolar component can be compensated by an additional hexapole after the first beam line focusing solenoid. The hexapole has to be rotatable in azimuthal direction and moveable in longitudinal direction. For a good correction the beam needs to have such a radial phase space distribution, that the force given by this hexapole acts on the aberrated beam exactly in such a way that it create a linear distribution after that corrector.

INTRODUCTION

The ion beam extracted from an ECRIS suffers from the magnetic field designed for a good confinement of the plasma. Both magnetic field components, the solenoidal part and the hexapolar part have influence on the properties of the ion beam. Whereas the error caused by the solenoidal component can only be shifted between different projections of the 4d-phase space[1, 2], the negative influence of the hexapole should be possible to be removed. The solenoidal component will stay with the beam, because ions are born within the plasma where the magnetic flux density is high, and therefore $\int \vec{B}ds \neq 0$ which is responsible for twisted trajectories. The experimental evidence for the density structure within the beam has been demonstrated by viewing targets and by emittance measurements with a suitable device[3, 4], showing a typical behavior for all ECRIS beams[5]. This can be explained when ions are extracted only on magnetic field lines going through the extraction hole[6]. A picture behind a pepper plate shows also experimental evidence of a certain structure, see Fig. 1.

The idea of compensation relies on the assumption that it is possible to set the ion beam profile within the known field of a hexapole in such a way that the actual field reverse the aberration of the incoming beam. For the compensation it is essential that the ion beam can be matched in phase space relative to the hexapole position. The orientation of the hexapole correction needs to be variable as well.

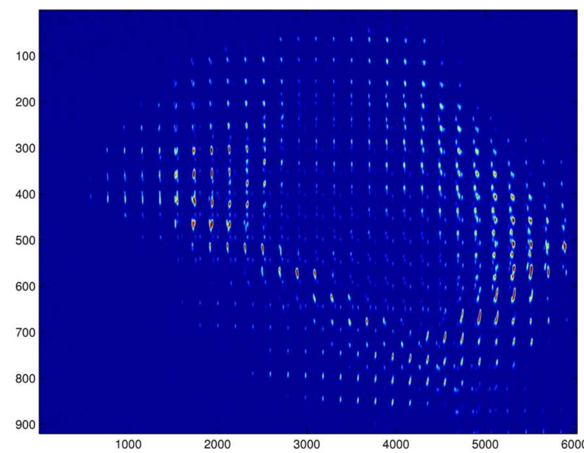

Figure 1: Beam spots behind a pepper plate. The $^{40}Ar^{8+}$ beam is extracted in cw-mode by a single hole of an accel-decel extraction system with 15 kV/-2kV. Both axis are scaled in pixel.

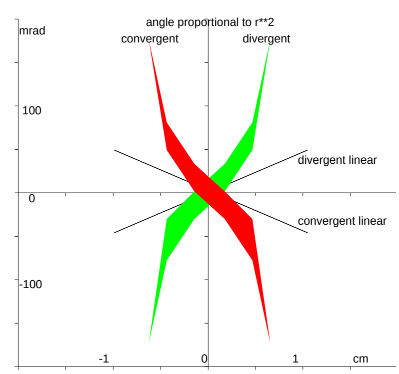

Figure 2: Both possible beam emittance orientations to remove the hexapolar error: divergent emittance in green, and the convergent emittance in red.

If the angle of the radial profile increases with r^2 as shown in Fig. 2, a hexapolar field can be used to change it to a linear distribution again. Such a setting should be possible to create by the help of the focusing force of the solenoid and its distance to the hexapolar field. However, this model assumes linear optic without any coupling. If the radial position of a trajectory changes within the compensation hexapole, the integral focusing force will apply. To minimize possible errors, the hexapole field should be as short as possible. The effective length has to be chosen such that the device can be designed with normal con-

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ducting coils. Additional simulation should verify these assumptions.

SIMULATION

To perform a simulation of such a system, the 3d code KOBRA3-INP[7] has been used. The computation has been made in several steps:

1. Simulation of extraction region including the plasma chamber for correct starting conditions of trajectories. The starting location is where the plasma confinement is weakest. The full charge state spectrum has been assumed to produce a correct solution of Poisson's equation within the extraction system. The electron density close to the plasma potential has been solved analytically. Plasma potential, particle density, and electron temperature have to be defined by the user. The space charge of the drifting ion beam is assumed to be compensated by electrons. These electrons are generated by collisions of primary ions with residual gas atoms and will be trapped in the space charge potential, whereas the secondary ions are repelled from this potential. Only one charge state has been saved for further transport simulation in a second area of simulation.

2. For the simulation of the optical section of the beam line, shown in Fig.3 with drift, magnetic solenoid, hexapole correction, it is necessary to use all six phase space coordinates for each trajectory (path of the particle) to take correlation effects into account. The distribution of the magnetic flux density has been calculated with an integral method, saturation effects are neglected. The hexapole is added analytically to the solenoid field. The hexapole component by its own is shown in Fig. 4.

3. For diagnostic reason, different projections of the six dimensional phase space are used. Here we investigate whether the projection of the six dimensional phase space can be used, or a more resolved quantity should be used instead. Projections were made with an additional slit perpendicular to the axis of the measurement to develop the charge density at a local spot in space. This is shown in Fig. 5: the first line shows the integrated emittance, whereas in the following lines a slit is moved in perpendicular direction to obtain spatial resolution. In each line the actual fraction of the beam is shown in real space (y-z) together with both projections y-y', and y-z'. The next three pictures in each line show the same for the perpendicular direction y-z, z-z', and z-y'. Beam direction x.

4. The assumption of a constant phase space volume along the beam line is correct, but it is valid in the six dimensional phase space only. Whether projections of this phase space show similar behavior needs to be proven in each specific case. In case of any coupling between these sub spaces the projection is not necessarily an invariant. Space charge force and magnetic force are examples for coupling forces.

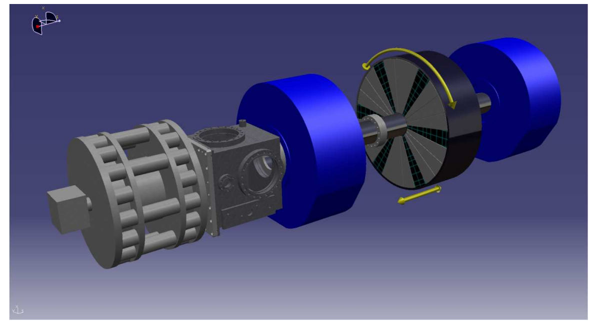

Figure 3: Top: artist view of the compensation device.

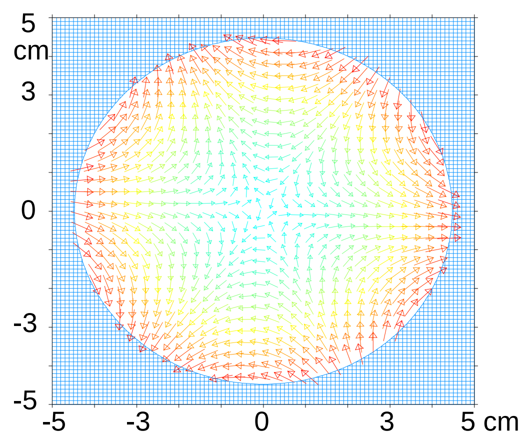

Figure 4: Cross section of the beam tube at the location of the hexapole. Arrows show the strength and the direction of the magnetic flux density.

Different intermediate states of focusing of the extracted ion beam by the solenoid are shown in Fig. 6. Using the particle distribution given by the simulation of the extraction system a slightly different behavior of the ion beam has been found compared to the experimental results. Whereas the hollow beam structure is present if the beam is under focused on the target, the appearance of three arms when over focused are not as visible in this simulation as experimentally observed.

There is a clear structure on the simulated beam, however, it does not depend on r^2 and this error cannot be corrected. Possible reasons to fail the required beam parameter in the simulation could be, that the hexapolar field combined with the solenoidal field will cause another error than a sequential application of both fields separately (coupling), or the initial energy of ions within the plasma differs from expected values and might depend on the origin of ions. Assuming higher starting energy of the ions in simulation seems to increase the effect caused by the hexapole.

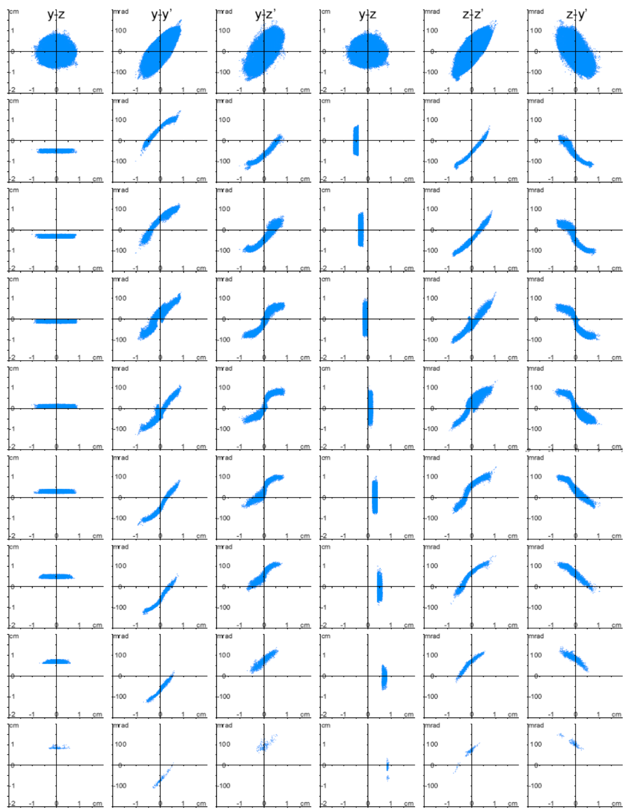

Figure 5: Different diagnostic: first line: real space, phase space, mixed phase space projection, for both transverse directions. Next lines: additional vertical respectively horizontal slit. Behind solenoid at x=0.7 m.

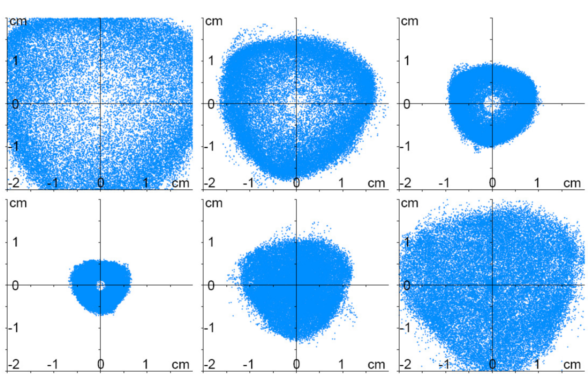

Figure 6: Influence of increasing focal strength of the solenoid on the ion beam profile. The beam is hollow if under focused (first line, focusing force 76%, 83%, and 90%), and becomes triangular afterwards (second line, focusing force 96%, 103%, and 110%).

At that time experiments with frequency ramping were made with the CAPRICE at the EIS test bench[8], showing a strong influence of the frequency on the extracted beam. In these experiments the beam shape on target can be interpreted as fixed surface or volume, containing a local ion density defined by the frequency. The dependence clearly verifies the assumption that collisions within the plasma are not important for the path of the ions. Otherwise these structures clearly defined within the plasma chamber before extraction would not be visible after the beam transport.

CONCLUSION

If the beam is correctly matched to a compensation hexapole, an emittance reduction due to straightening of the emittance figure seems to be possible. A change of the radial position of a trajectory within the hexapole modifies the action of the hexapole. This effect should be avoided, therefore a shorter and stronger hexapole seems to be more useful rather than a weaker but longer one. A normal conducting hexapole seems to be sufficient, but this depends on the required radius.

The simulation of the problem is not an easy task, because already the properties of the extracted beam depend on several parameters, which require always the full scan of computation (variation of each parameter). The optical matching condition to the compensator again will require to scan all optical parameters for the full range.

The strong influence of frequency ramping on the extracted beam indicates that the model in the simulation is still not perfect; the interaction of frequency, geometry, and plasma is neglected in the simulation, which is not acceptable according to the experimental results. The influence of the microwave on the starting conditions of ions needs to be formulated.

REFERENCES

[1] J. Reich, H. Beuscher, FA Jülich, R.K. Bhandari, Bhaba ARC, J.I.M. Botman, H.L. Hagedoorn, Eindhoven University, Partial beam decorrelation of sources providing ions out of axial magnetic fields, EPAC 1988, Rom, Italy.

[2] J.I.M. Botman, H.L. Hagedoorn, Eindhoven University, J. Reich, FA Jülich, The beam emittance of cyclotrons with an axial injection system, EPAC 1988, Rom, Italy.

[3] J.P.M. Beijers, H.R. Kremers, V. Mironov, J. Mulder, S. Saminathan, and S. Brandenburg, Ion source development at KVI, RSI Vol. **79** No 2, 2008.

[4] L. Panitzsch, M. Stalder, R.F. Wimmer-Schweingruer, Direct high-resolution ion beam-profile imaging using a position-sensitive Faraday cup array, Review of Scientific Instruments, Vol. **80**, 113302, 2009.

[5] P. Spädtke, R. Lang, J. Mäder, J. Roßbach, K. Tinschert, GSI Darmstadt, Beam transport effects for ECRIS, Proceedings of LINAC08, Victoria, BC, Canada

[6] P. Spädtke, K. Tinschert, R. Lang, J. Mäder, J. Roßbach, GSI Darmstadt, J.W. Stetson, MSU Michigan, L. Celona, INFN Catania, Prospects of Ion Beam Extraction and Transport Simulations, RSI Vol. **79** No 2, 2008.

[7] KOBRA3-INP, Junkernstr. 99, 65205 Wiesbaden, Germany.

[8] F. Maimone, K. Tinschert, P. Spädtke, J. Mäder, J. Roßbach,, R. Lang, GSI Darmstadt, L. Celona, INFN-LNS Catania, Microwave frequency dependence of the properties of the ion beam extracted from a CAPRICE type ECRIS, these proceedings.