BEAM TRANSPORT EFFECTS FOR ECRIS

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ION BEAM EXTRACTION

Experimental results from ion beams, extracted from an Electron Cyclotron Resonance Ion Source (ECRIS) are compared with the model used for simulation, which has to taken into account that the energy of ions within the magnetically confined plasma in a trap of several T is in the eV-range. Electrons do have a different energy distribution: there are hot electrons up to MeV range, but also low energy electrons, responsible for charge neutrality within the plasma. Because the gyration radius of ions is within the sub-mm range, ions can be extracted only if they are located on a magnetic field line which goes through the extraction aperture. Ion-ion collisions are not important for the path of the ion. Because of the gradient dBz/dz of the mirror field only these ions can be extracted, which have enough energy in direction of the field line. These conditions are fulfilled for ions which are going to be lost through the loss cones created by the hexapole. The extracted beam shows a typical behavior for any ECRIS: when the beam is focused by a lens (here a solenoid) directly behind extraction, the initial round and hollow beam develops wings with a 120-degree symmetry. Because of these considerations, the magnetic flux density in the plane of extraction is a good approximation for the minimum required flux density from which ions can be extracted. This surface is shown in 2D-cuts for two different ECRIS types (see Fig. 2 to Fig. 6). It is assumed that the plasma generator is able to produce particles in the required charge state at these locations. The model has been tested for different existing ion sources, and for ion sources which are still under design or under construction.

CAPRICE

This source, routinely in operation at GSI, has been used together with the technique of viewing targets, to proof our model for ion beam extraction. The ion source has two normal conducting coils for the mirror trap and a hexapolar device created by permanent magnets. Using different materials for these permanent magnets, we have had tested three differently strong hexapolar fields: 0.8 T, 1.0 T, and 1.2 T measured always at the plasma chamber. Whereas the transverse magnetic flux density is fixed when the hexapole has been installed, the mirror field for both mirror coils is variable up to 1.2 T on axis. By changing the current in the mirror field coils on injection side and extraction side, the location of extraction can be changed from the back side of the source to the radial location of the loss lines, starting at injection side and going to about the center between both coils. Because the allowed starting conditions are different for different magnetic settings, it is important for ECRIS extraction simulation to use the actual used magnetic fields. An example is shown in Fig. 9 for the 1 T hexapole.

SUPERNANOGAN

This commercial available source[1] is much easier to simulate, because the magnetic flux density is frozen, which might be a disadvantage on the other side. The magnetic flux density has been calculated using the PANDIRA code[2]. This program calculates the cylinder symmetric mirror field, created by permanent magnets only. The hexapolar field has been added in the 3D-map required for the KOBRA3[3] simulation analytically. Because of the permanent magnets, the longitudinal flux density component changes sign within the extraction.

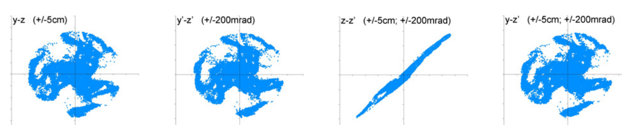

Figure 1: Different projections of the 6D phase space from left to right: beam cross section, momentum space, emittance, mixed phase space. Total current for the simulation 3 mA, shown is one charge state only.

ARC-ECRIS

This is an already old idea from plasma-fusion science [4], using a curved coil to produce the required magnetic configuration. Because of this simple design, the idea has been re-invented [5] to check the performance of such a source. This device creates a minimum $|\vec{B}|$ structure with a quadrupole like loss cones, shown in Fig. 2. If the plasma generator provides a comparable charge state distribution as regular ECRIS it would be a promising alternative, see Fig. 3.

MS-ECRIS

This source has been designed within a European collaboration[6]. It consists out of three solenoidal coils to produce the mirror field and a set of coils for the hexapole, designed to be 2.7 T at the plasma chamber. Depending on

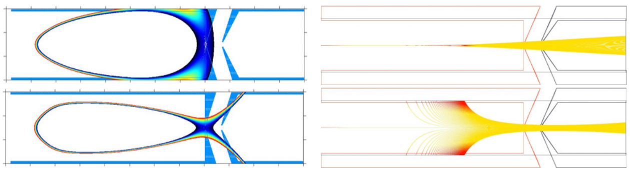

Figure 2: Magnetic structure of the arc-ecris: lines of constant $|\vec{B}|$ and magnetic field lines in horizontal and in vertical projection.

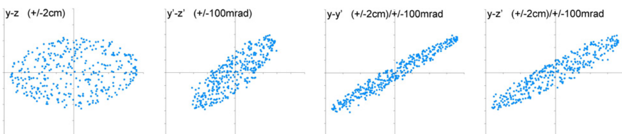

Figure 3: Different projections of the 6D phase space for the beam extracted from ARC-ECRIS: real space, momentum space, emittance, and a mixed phase space. In this solution, space charge effects are still neglected.

the polarity and strength of the middle solenoid, the extraction area can be changed from the back side of the source to the radial loss lines, see Fig. 4.

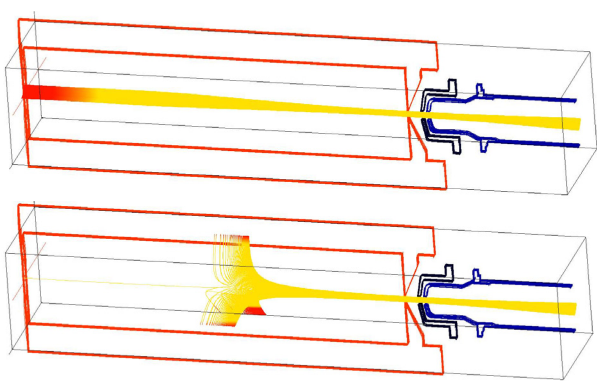

Figure 4: Magnetic field lines for different coil settings of the MS-ECRIS. Top: design value, middle coil switched off. Bottom: design values, injection field decreased to 60%. The red part of the field line indicates that the value of flux density is above that value at extraction aperture.

A-Phoenix

This source[7] has a hybrid set up: two superconducting coils form the mirror field. The minimum between both coils can be slightly modified by an additional normal conducting coil. The hexapole is made by permanent magnets. For this simulation we have used the standard hexapole design with 1.83 T at 65 mm radius. The position of the extraction electrode is far away from the maximum field of the mirror coil on extraction side. This might have been enforced by the small diameter of the plasma chamber, see Fig. 5. Positioning of the electrode at that point lowers the magnetic flux density at extraction.

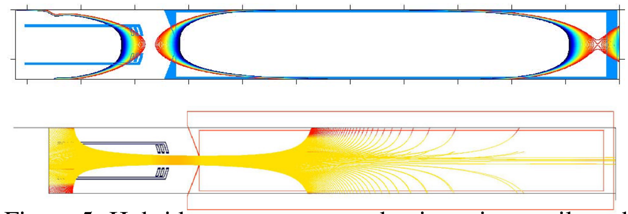

Figure 5: Hybrid source: superconducting mirror coils and permanent magnets for the hexapole.

SECRAL

This source[8] has a reversed position between solenoid and hexapole. Here the hexapole is inside the solenoids. This was decided for technical reasons, especially due to the forces between solenoid and hexapole, extraction condition has been found to be very good, see Fig. 6.

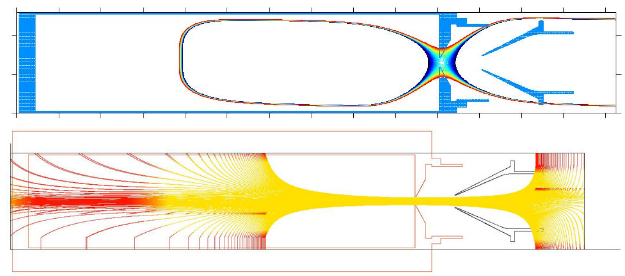

Figure 6: Magnetic field lines and magnetic flux density for the SECRAL ion source.

RIKEN 28 GHz

The Riken version of a 28 GHz ECRIS[9] includes the possibility to bias the beam line, giving the opportunity to increase beam energy without having the source on extensive high potential, see Fig. 7. The advantage is the smaller emittance for the beam transport with higher energy, according to Liouville. The space charge compensation is not affected. When connecting the beam line again to ground, decelerating the beam, the emittance will increase again. Screening just before decelerating is required, otherwise the space charge compensation would be lost due to extracting electrons from the beam.

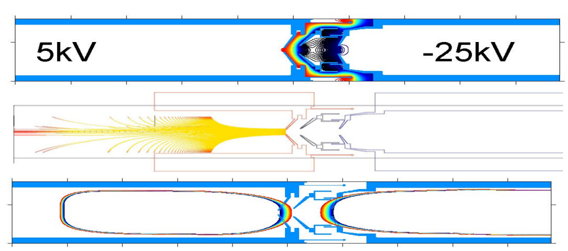

Figure 7: Superconducting ECRIS from Riken: top: electric potential, middle: magnetic field lines, bottom: lines of constant $|\vec{B}|$.

BEAM LINE SIMULATION

Different numerical methods can be used to simulate the transport of an ion beam. The choice is from simple matrix formalism to time dependent particle in cell with exact calculation of forces. It depend on the specific problem to be investigated which type of program has to be used. If the computational results represent the experimental observations, it can be concluded that the applied model can describe the experimental observations sufficiently well. In the simulation for the beam line which has been described in [10], we use all phase space coordinates of each particle obtained from the extraction simulation. The beam transport is made by a matrix formalism using the full 6×6 matrix, including coupling elements for each particle individually[11].

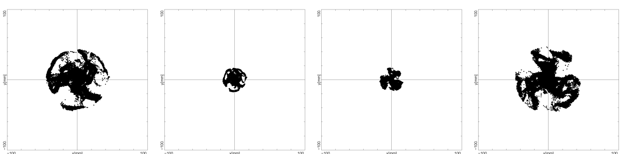

Figure 8: Beam cross sections from SUPERNANOGAN behind the beam line solenoid with increasing magnetic focusing strength from left to right.

The experimental results can be reproduced, using the linear transformation only and neglecting space charge effects. It seem that all peculiarities are defined by the initial particle distribution.

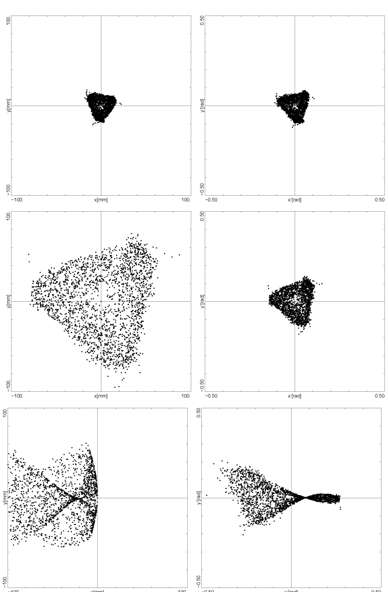

Figure 9: Beam profile (left) and momentum space (right) from CAPRICE with 1.0 T flux density hexapole, after extraction (first row), behind a focusing solenoid (second row), and after m/q separation (third row).

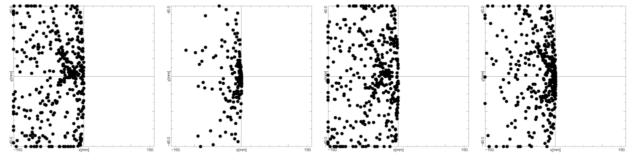

Figure 10: Expected beam cross sections behind the dipole for different magnetic settings of MG-ECRIS.

CONCLUSION

Experimental results which have been described in [12] could be reproduced by the used model. One main result, which have been obtained with the CAPRICE, was that the cross section of each different extracted m/q ratio changes from a hollow triangular ring to a three-wing structure when the specific m/q becomes over-focused with decreasing m/q in the stray field of the source. The cross-section of each m/q ratio, starting with m/q= 1 focused by a beam line solenoid located directly behind extraction shows similar behavior. Behind the dipole a structure is obtained, which had already been defined inside the plasma chamber. We can conclude from that, that space charge of the dc beam along the beam line is compensated to a very high degree.

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