Low Energy Beam Transport for Ion Beams created by an ECRIS

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Abstract

It has been shown previously that the emittance of an ion beam, extracted from an Electron Cyclotron Resonance Ion Source (ECRIS) is determined by magnetic field, applied electric potentials, geometry, and particle density distribution together with the initial properties of these particles[1],[2].

The model used for computer simulation seems to fit the experimental results: ions are extracted from the ion source if they are created (started) at places where magnetic field lines are going through the extraction aperture. Furthermore, the absolute value of magnetic flux density relative to the flux density at the extraction aperture defines, whether this ion can be extracted or not.

Due to coupling between the different subspaces of phase space because of the magnetic field, several assumptions used for beam transport issues are not valid any more: for example, two-dimensional emittance does not stay constant in every case; the six dimensional phase space does.

With increasing extracted ion currents, space charge compensation of the extracted beam becomes an important issue. The beam itself will create secondary particles which can serve for space charge compensation. This compensation will build up in a relatively short time, depending on the pressure, as long no leakage is present within the beam line.

ION BEAM EXTRACTION

Electron cyclotron resonance ion sources (ECRIS) are used more often, especially since several improvements of this type of ion source had increased the available intensities even for higher charge states. Nevertheless, extraction and beam transport is only partially comparable to the case of ion beam extraction not influenced by magnetic fields. It seems that the starting conditions of the ions within the plasma are essential for the process of beam formation. Because of the low ion temperature which is in the low eV range and the high magnetic flux density up to several T, the Larmor radius of ions is in the sub-mm range. Therefore, ion-ion collisions are minor important for the path of the ion. The magnetic field lines going through the extraction aperture show the possible path for the ions to be extracted. If the magnetic flux density is increasing along the field line, particles will transform energy in direction of the field line into rotational energy perpendicular to the field line and visa versa. Only if it is possible to create ions at these locations or to transport them to these places with a certain magnetic flux density, the ion can be extracted. The magnetic flux density in the plane of extraction is therefore a good approximation for the minimum required flux density from which ions can be extracted. This surface is shown in the following 2D-cuts for different ECRIS types, see Figures 1, 2, 4 - 10. Together with the information where the magnetic field lines going through the extraction aperture are coming from, the possible extraction area can be determined. 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 in construction, and it has been found that the actual magnetic setting has to be taken into account, instead of using the design values only.

CAPRICE

This source, used at the accelerator facility at GSI, has been investigated together with the technique of viewing targets, to proof our estimates about beam extraction. The ion source has two normal conducting coils for the mirror trap and a hexapole, made of permanent magnets. Using different materials for these permanent magnets, we have tested three differently strong hexapolar fields: 0.8 T, 1.0 T, and 1.2 T, measured at the inner diameter of 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, see Fig. 1. Plasma heating is done by a 14.5 GHz klystron. By changing the mirror field on injection side or extraction side, the origin of extracted ions can be changed from the back side of the source to the radial location of the loss lines, starting at injection side and reaching the center between both coils, see as example Fig. 7 for the MS-ECRIS. Because the allowed starting conditions are determined by the magnetic settings, it is important for ECRIS extraction simulation to include the different possible magnetic fields.

SUPERNANOGAN ©

This commercially available ion source[3] is easier to simulate, because the magnetic flux density is frozen due to the only use of permanent magnets, which might be a disadvantage on the other side. The magnetic flux density has been calculated using the PANDIRA code[4], which calculates the rotational symmetric mirror field. Because of the usage of permanent magnets, the longitudinal field

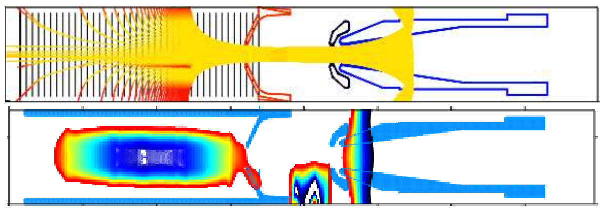

Figure 1: Magnetic field lines for Caprice, equipped with the 1.0 T hexapole, and corresponding lines of constant $|\vec{B}|$.

component changes sign within the extraction. The hexapolar component has been added in the 3D-map required for the KOBRA3 [5] simulation analytically, see Fig. 2. The extracted beam is shown in Fig. 3.

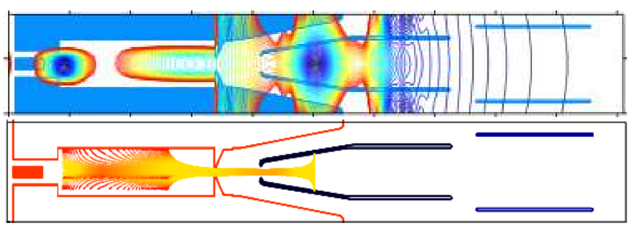

Figure 2: Magnetic flux density distribution in the SUPERNANOGAN: top: lines of constant $|\vec{B}|$ in mid-plane, bottom: magnetic field lines in projection.

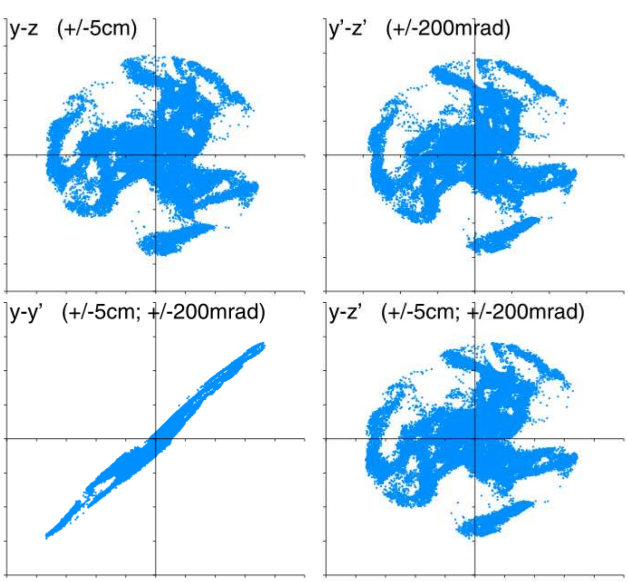

Figure 3: Different projections of the 6D phase space for the beam extracted from SUPERNANOGAN: top left: beam cross section, top right: momentum space, bottom left: emittance, bottom right: mixed phase space. Total current at 24 kV extraction voltage is 3 mA for oxygen, Only O^{3+} is shown here.

ARC-ECRIS

This is an old idea from plasma-fusion science [9], using a curved coil to produce the required magnetic configuration for a stable plasma confinement, which is reinvestigated for ion source application[8]. This device creates a minimum $|\vec{B}|$ structure with quadrupole like loss cones, see Fig. 4.

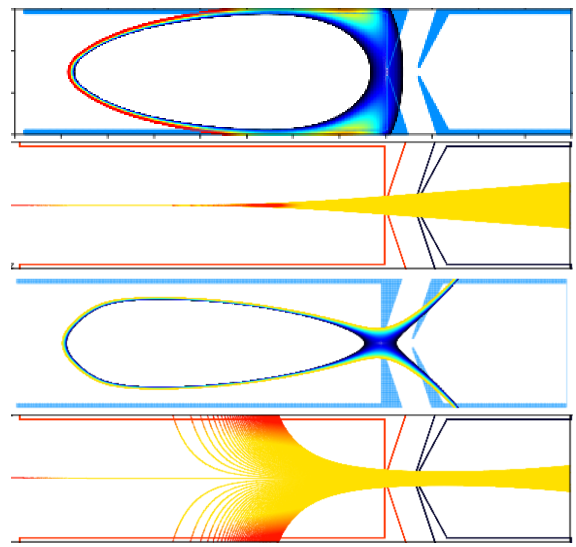

Figure 4: Magnetic structure of the arc-ecris: lines of constant $|\vec{B}|$ and magnetic field lines in horizontal and in vertical projection.

The extracted beam, shown in Fig. 5 favors a beam line with quadrupoles. If the properties of the plasma generator are as good as for regular ECRIS, this could be an interesting alternative.

MS-ECRIS

This superconducting 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. Because the magnetic structure is important for the possible starting conditions, simulations have to be made for all the different possible magnetic settings, see Fig. 6. Depending on the polarity and strength of the middle solenoid, the extraction area can be changed from the back side of the source (flat field mode) to the radial loss lines (high B mode). The question remains, whether the plasma generator is able to produce the ions which would be possible to extract. For plasma heating a 28 GHz gyrotron device is foreseen.

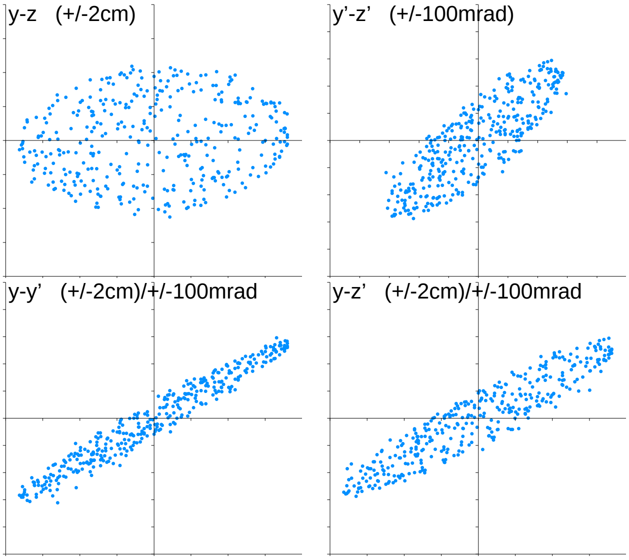

Figure 5: Different projections of the 6D phase space for the beam extracted from ARC-ECRIS: real space, momentum space, emittance, and a mixed phase space. In this solution, space charge effects are still neglected.

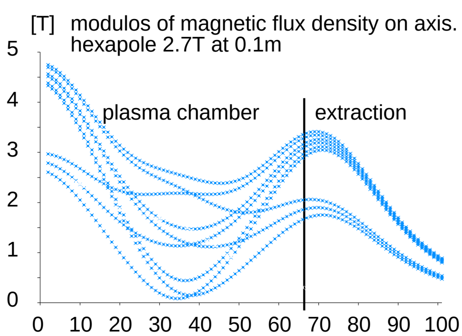

Figure 6: Different magnetic flux density on axis for the MS-ECRIS, used for the simulation necessary to determine extraction conditions for each hexapole setting.

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 diameter. The position of the extraction electrode is far away from the maximum field of the mirror coil on extraction side, see Fig. 8. Positioning of the electrode at that point selects a lower magnetic flux density on axis at extraction, having influence on the extractable ions. If the electrode would be close to the position of maximum flux density, the plasma chamber seems to be too small for an effective extraction.

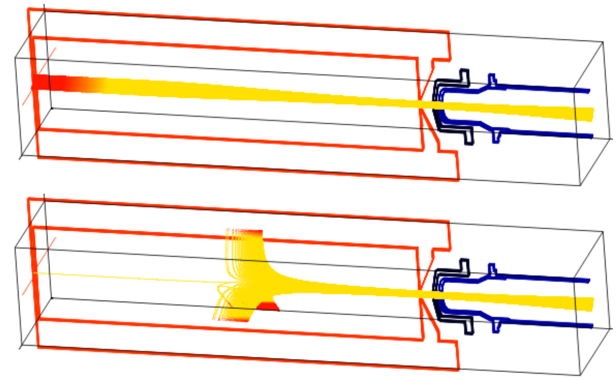

Figure 7: Magnetic field lines for different coil settings of the MS-ECRIS. Top: design value, middle coil switched off. Bottom: design values, injection field decreased to 60%. The red part of the field line indicates that the value of flux density is above that value at extraction aperture.

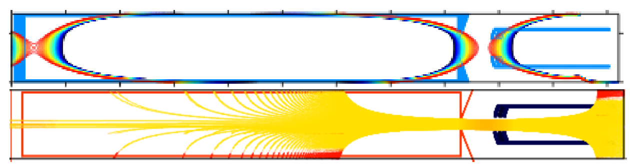

Figure 8: Magnetic field lines and magnetic flux density for the A-PHOENIX ion source.

SECRAL

This source[11] has a reversed radial position of solenoids and hexapole. Here the hexapole is outside the solenoids. This was decided for technical reasons, especially due to the forces between solenoid and hexapole.

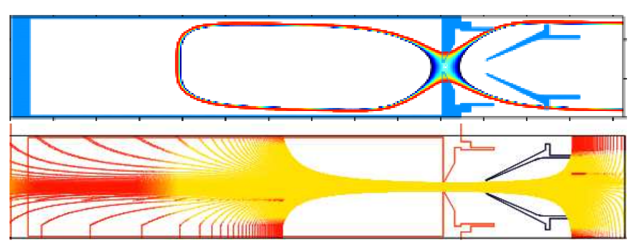

Figure 9: Magnetic field lines and magnetic flux density for the SECRAL ion source.

The magnetic flux density distribution shows good conditions for extraction, see Fig. 9.

RIKEN 28 GHz

The Riken version of a 28 GHz ECRIS [12] 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. 10. 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.

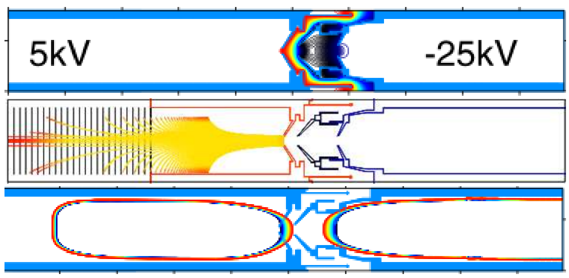

Figure 10: Superconducting ECRIS from Riken: top: electric potential, middle: magnetic field lines, bottom: lines of constant $|\vec{B}|$.

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 codes with exact calculation of forces. It depends on the specific problem to be investigated which type of program has to be used. However, if the computational results represent the experimental observations, it can be concluded that the applied model describes the experimental observations sufficiently well. In the simulation of the beam line shown in Fig. 11 we use all phase space coordinates of each particle obtained from the extraction simulation.

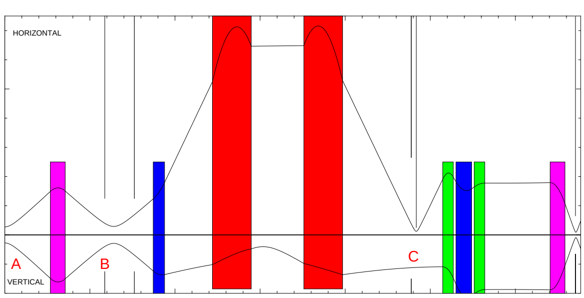

Figure 11: Beam line from left to right: solenoid, quadrupole singlet, split dipole, quadrupole triplet, solenoid. Top: horizontal dispersive plane, bottom: vertical. Envelope for 300π mm mrad, no correlation. A, B, C denotes the three locations where the beam is shown in figures 12 - 16.

Beam transport itself is made by a matrix formalism using the full 6×6 matrix, including coupling for the different optical elements, for each particle individually, not only for the ellipse parameter.

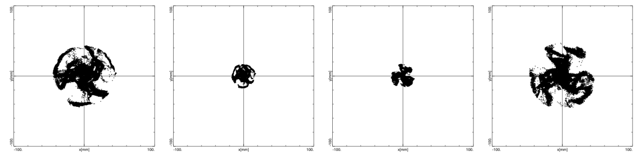

Figure 12: Beam cross sections from SUPERNANOGAN© behind the beam line solenoid (position B in Fig. 11) with increasing magnetic focusing strength from left to right.

The experimental results can be reproduced, using a linear transformation without space charge effects, see Fig. 13. From that fact we conclude a reasonable degree of space charge compensation.

Having shown that this transformation is consistent with experimental results, the same transformation can be applied to different ion sources or to different ion source operating conditions, see Fig. 15,16.

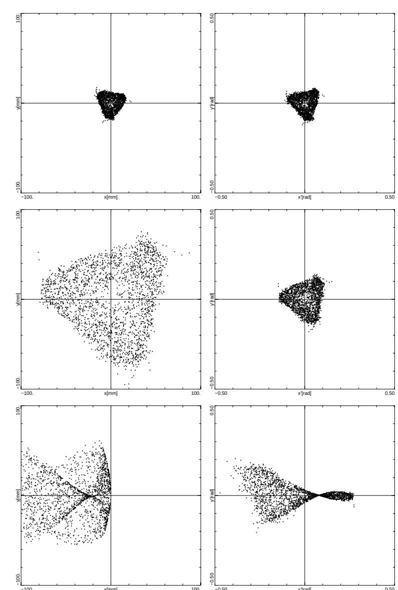

Figure 13: Beam from CAPRICE, equipped with the 1.0 T hexapole. Top: after extraction, starting conditions for MIRKO (position A in Fig. 11). Middle: behind the first beam line solenoid (position B in Fig. 11). Bottom: behind the dipole in the plane of resolving slits (position C in Fig. 11). Left column: real space ±100 mm full scale. Right column: momentum space ±500 mrad full scale.

Space Charge

The extracted positive ion beam creates a positive electric potential with a value given by the number of particles and their velocity. If the potential becomes high enough it will influence the path of the extracted beam itself. On the other side such a potential acts as a trap for electrons which are created in collisions of the primary beam ions

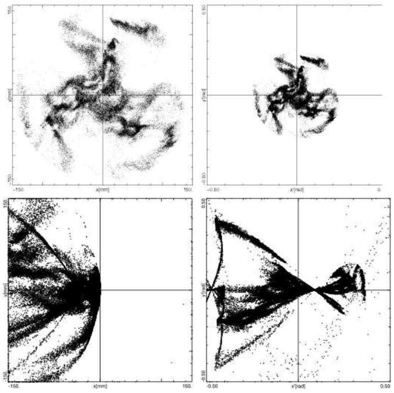

Figure 14: Beam from SUPERNANOGAN. Starting conditions are shown in Fig. 12). Top: behind the first beam line solenoid (position B in Fig. 11). Bottom: behind the dipole in the plane of resolving slits (position C in Fig. 11). Left column: real space ±150 mm full scale. Right column: momentum space ±500 mrad full scale.

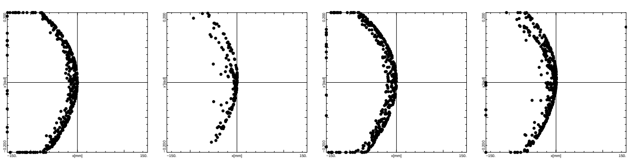

Figure 15: Unmatched emittances behind the dipole in the dispersive plane for different magnetic settings of MS-ECRIS. ±150 mm, ±200 mrad full scale.

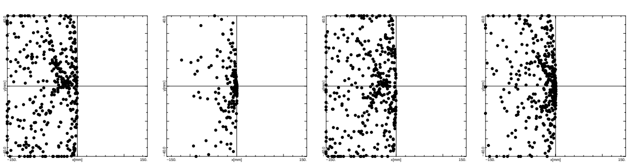

Figure 16: Beam cross sections behind the dipole for different magnetic settings of MS-ECRIS. horizontal ±150 mm, vertical ±40 mm full scale (position C in Fig. 11).

with residual gas atoms. The specific kind of trap might change along the beam line, as for example from a drift section with a pure electrostatic beam plasma to a bending section with a magnetic beam plasma. The movability of electrons within these elements is high only in the magnetic field direction, restricted in the transverse direction. If there are no leakages for electrons it is a question of time only until this potential will be compensated down to the range of the electron temperature. Leakages are given by electric fields similar to the extraction, or dc post-acceleration columns, but already a beam tube, which is not properly grounded, might remove electrons from the space charge compensation. These leakages have to be screened if they cannot be removed.

EXPERIMENTS

All experimental results have been described in [1]. One main result, which has been obtained with the CAPRICE, was that the cross section of each different extracted mass to charge ratio m/q 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, see Fig. 17.

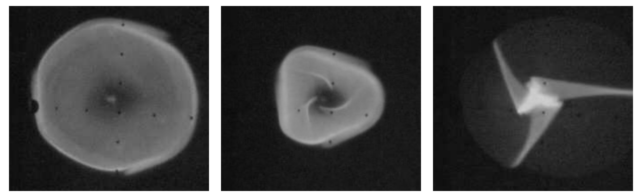

Figure 17: Measured beam profiles from CAPRICE at location B with increasing focusing strength of the beam line solenoid. Only one m/q is visible, all other are de- or over focused. Starting from m/q=1 all different ratios show the same behavior when focused.

Another result was that 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.

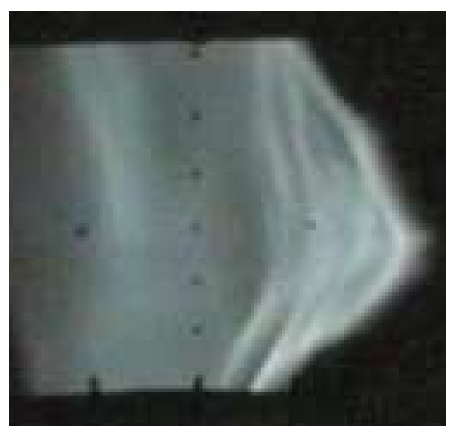

Figure 18: Measured beam profile from CAPRICE at location C.

CONCLUSION

We have shown, that the ion beam extracted from an ECRIS is affected by the magnetic field. The effects have been shown in experiment as well as in simulation. We do conclude that the effects observed with ECRIS beams are given by correlation of particles inside the plasma and by all resulting forces during extraction itself. The extraction can be simulated using a fully 3D code with the usual space charge compensation described by Self[14].

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