THE BEAM EMITTANCE OF CYCLOTRONS WITH AN AXIAL INJECTION SYSTEM

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Abstract

Axial magnetic fields in ion sources cause an enhancement of the emittances in the transverse phase planes. Ion beams started from a source without axial magnetic field will show emittance enhancement when entering axially into the magnetic field of a cyclotron. However in both cases there exists a strong coupling between the two phase planes. These phenomena will be treated analytically. It is shown that the correlation may be cured by special devices in the beam handling system or by the specific inflection-system. For an ECR source the emittance can be drastically reduced in one phase plane by more than an order of magnitude while in the other phase plane the emittance enhances by a factor 2. The 4-dimensional emittance is then again determined by the transverse ion temperature and the size of the hole. The hyperbolic inflection is taken as a main example. A few remarks are made about the mirror inflector.

Introduction

An axial injection system delivers a beam with a well defined area in phase space into a cyclotron central region. However, one must be aware of the fact that axial magnetic fields may cause a strong correlation between the phase spaces in the three dimensions. This point is valid for external ion sources with or without an axial magnetic field. It was shown (1,2) by theory and experiment that the initial correlation, when using an ECR source, can be eliminated partially in the beam guiding system to the axial injection system of a cyclotron. In this paper it is demonstrated that a complete decorrelation can be made in such a way that for zero transverse ion temperature the emittance in one transverse phase plane is shrunk to a point, while the emittance in the other plane remains increased by a factor 2. Using a hyperbolic inflector (3) this property can be maintained in the cyclotron centre. The combination of this inflector and the axial magnetic field shows a transport matrix having a separated action on the two transverse phase planes. This seems not to be true for a mirror. Therefore in this last case the coupling between the phase planes due to the axial cyclotron field may lead to an emittance enhancement, when starting from an ion source without axial magnetic field. The already existing coupling when using an ECR source then may be helpful to avoid an extra emittance enhancement. For the injection into the cyclotron centre several systems are used: the mirror (4), the spiral inflector (5), the hyperbolic inflector (3). In the Julic cyclotron (6) the hyperbolic inflector is used. The theory in this paper is mainly applied to this last type of inflector. It has the nice property of an electrical field which can be easily described in an analytical shape. Therefore also the ion optics can be presented in a nice way (7,8). Furthermore the optical behaviour is linear to a high degree. The entrance and exit of the hyperbolic inflector cause a small non linear behaviour.

The Motion in an Axially Symmetrical Magnetic Field

The motion in an axially symmetrical magnetic field can be considered as the result of two equal lens actions in the transversal phase spaces for a coordinate system rotating with half the local cyclotron frequency (1,9). As the ECR source generally has a cyclindrical exit aperture and as any arbitrary rotation can be made by solenoids without affecting in linear order the ion optics in a beam guiding system we neglect the rotation of the coornate system in our treatment. The representation of the transport through the solenoid for ions entering and leaving the field thus becomes:

$$\begin{pmatrix} x_f \\ x'_f \\ y_f \\ y'_f \end{pmatrix} = \begin{pmatrix} m_{11} & m_{12} & 0 & 0 \\ m_{21} & m_{22} & 0 & 0 \\ 0 & 0 & m_{11} & m_{12} \\ 0 & 0 & m_{21} & m_{22} \end{pmatrix} \begin{pmatrix} x_i \\ x'_i \\ y_i \\ y'_i \end{pmatrix}$$

If the particles start inside the magnetic field and then leave it, we have to take into account that the divergencies have to be replaced by the canonical momenta. This is done by applying a correlation matrix on the above given inital vector.

$$R = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & -\frac{1}{2R_s} & 0 \\ 0 & 0 & 1 & 0 \\ \frac{1}{2R_s} & 0 & 0 & 1 \end{pmatrix}$$

where R_s represents the cyclotron radius in the source field at the extraction hole. The sign of R_s depends on the direction of the magnetic field. Thus

$$\underline{x}_f = M \cdot R \cdot \underline{x}_i$$

For the reverse action i.e. starting the particles outside the magnetic field and then observing them inside the field one has

$$\underline{x}_f = R^{-1} M \underline{x}_i$$

Not taking into account the matrix R^{-1} means that we have the canonical momenta instead of the kinetic momenta.

The Emittance of the ECR Source

Often the emittances of the ECR sources are measured separately in the transverse planes. These emittances are easily found by realizing that the determinants of the two sub matrices of the matrix M equal unity and that the entrance vector for this matrix is found by applying the correlation matrix on the vector $\underline{x}_i$:

Using the assumption $x'_i = 0 = y'_i$, which is not an essential assumption, one finds for the x-phase space the vector $(x_i, -y_i/2R_s)$. As x_i and y_i are variables on a circular area, representing the exit hole of the source, x_i and $y_i/2R_s$ describe an elliptical area yielding the emittance

$$\epsilon_x = \pi r_s^2 / 2R_s = \epsilon_y$$

in which r_s is the radius of the source aperture.

The same holds for the y dimension. This agrees quite well with experimental observations (10). However one has to realize that there exists a strong coupling between both phase planes, so that in fact the four-dimensional phase volume has to be taken. The determinants of R and M equal unity. The phase space volume thus becomes:

$$\epsilon_y \simeq 4\pi\, r_s^2 \frac{kTs}{qV_{extr}}$$

in which T_s is the transverse ion temperature in the source, V_{extr} is the extraction voltage and q is the charge state. The factor 4 accounts for positive and negative divergences. This 4-dimensional volume is the same as that one produced by a source without axial magnetic field having the same ion temperature and extraction voltage. To get optimal profit of any source one must avoid coupling between phase spaces in the cyclotron.

The hyperbolic inflector

The hyperbolic inflector together with the axial magnetic field shows a separated transfer of the transversal phase planes. Due to this an initial beam correlation will be transported to the cyclotron centre. A source without axial magnetic field can yield in this way the same emittances inside the cyclotron. This seems however a special property of the hyperbolic inflector. Using the matrices for a mirror as given by Bellomo e.a. (8) correlation inside the cyclotron is generated when outside an uncorrelated beam is availabe. The correlation of the outside beam then can help to overcome this problem. In the next seciton we will show a decorrelation device for an ECR source applied numerically for the Julich injection line.

Beam Decorrelation by means of Skew Quadrupoles

It was shown that a partial beam decorrelation could be made when an image of the ECR source hole is made in the middle of a skew quadrupole (1):

$$\begin{pmatrix} m_{11}x \\ 0 \\ m_{11}y \\ \dfrac{m_{22}x}{R_s} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & S_1 & 0 \\ 0 & 0 & 1 & 0 \\ S_1 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} m_{11} & 0 & 0 & 0 \\ 0 & m_{22} & 0 & 0 \\ 0 & 0 & m_{11} & 0 \\ 0 & 0 & 0 & m_{22} \end{pmatrix} R \begin{pmatrix} x \\ 0 \\ y \\ 0 \end{pmatrix}$$

with $S_1 = \frac{1}{2R_s}$.

By reversing the roles of the coordinates and momenta one observes that then the action of a second skew quadrupole generates a point area in the x-phase plane and an elliptical area of size $\pi r^2/R_s$ in the y phase plane. This role exchange is performed by a solenoidal lens which has its focal points in the middle of the two skew quadrupoles.

$$\begin{pmatrix} 0 \\ 0 \\ m_{22}xF \\ \dfrac{-m_{11}y}{F} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & S_2 & 0 \\ 0 & 0 & 1 & 0 \\ S_2 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 0 & F & 0 & 0 \\ -\frac{1}{F} & 0 & 0 & 0 \\ 0 & 0 & 0 & F \\ 0 & 0 & -\frac{1}{F} & 0 \end{pmatrix} \begin{pmatrix} m_{11}x \\ 0 \\ m_{11}y \\ \dfrac{m_{22}x}{R_s} \end{pmatrix}$$

$$S_2 = \frac{m_{11}R_s}{m_{22}F^2}$$

The decorrelation is complete now, resulting in an emittance in the y-phase plane $\epsilon_y = \pi r^2/R_s$ and a point area in the x-phase plane. As the total 4-dimensional phase space volume remains a constant we immediately derive the emittance in the x-phase plane for a non zero transversal ion temperature.

$$\epsilon_x = \epsilon_4/\epsilon_y = 4\pi \frac{r_s^2 kTs}{qV_{extr}} \Big/ \frac{\pi r_s^2}{R_s} = 4R_s \frac{kT_s}{qV_{extr}}$$

Application of Decorrelation in the JULIC case

As sketched in figure 1 a decorrelator for the superconducting ECR source consisting of two skew quadrupoles in the focus locations of a spherical lens has been fed into the ISIS beam guiding system [6] at a focus location to demonstrate the effect of complete decorrelation via TURTLE ray tracing for zero transverse ion temperatures. The first skew quadrupole decorrelates the phase space in one plane to a source of 2 cm width with zero divergence. The lens L transforms this object into a source of zero extent and ± 40 mrad divergence. The second skew quadrupole squeezes this phase space figure into one point. Figure 2 shows what happens to the beam right after the hyperbolic inflector in the median plane of the cyclotron. Varying the two skew quadrupoles tight together from -1 (arbitrary unit) in steps to +1 one can follow the successive increase and reduction from 0 to full and from full to 0 of the phase volumina in the horizontal (r,r') and the vertical (z,z') plane, respectively. Even with the higher order aberrations mainly coming from the bending plane of the beam guiding system one easily sees the factor of two in the phase volumina for SK1,2=0 compared to SK1,2= ± 1. If for SK1,2= -1 the transverse ion temperature is now gradually enhanced no change can be seen for the phase volumina in both planes for a transverse ion tempe- rature of 0.6 eV typical for ECR ion sources. For the (r,r') plane this of course is due to the finite cell size to gather particles in the scatter plot. For transverse energies of 3.6 and 14.2 eV the multiplication of the two phase space areas already reveals a four dimensional phase space volume corresponding to source hole radius and transverse temperature, thus proving the complete beam decorrelation.

Conclusion

It has been shown that a complete reduction of the beam emittance degradation effect due to the beam passage through falling or rising magnetic fields should be possible by applying beam decorrelation techniques. Especially the beam decorrelation using two skew quadrupoles in the focal points of a spherical lens might be a very effective tool to optimize the system for ion sources with axial magnetic fields injecting into a cyclotron for either optimum horizontal beam quality (SK = - 1, $\epsilon_r = 0$) or maximum intensity (SK = + 1, $\epsilon_z \to 0$).

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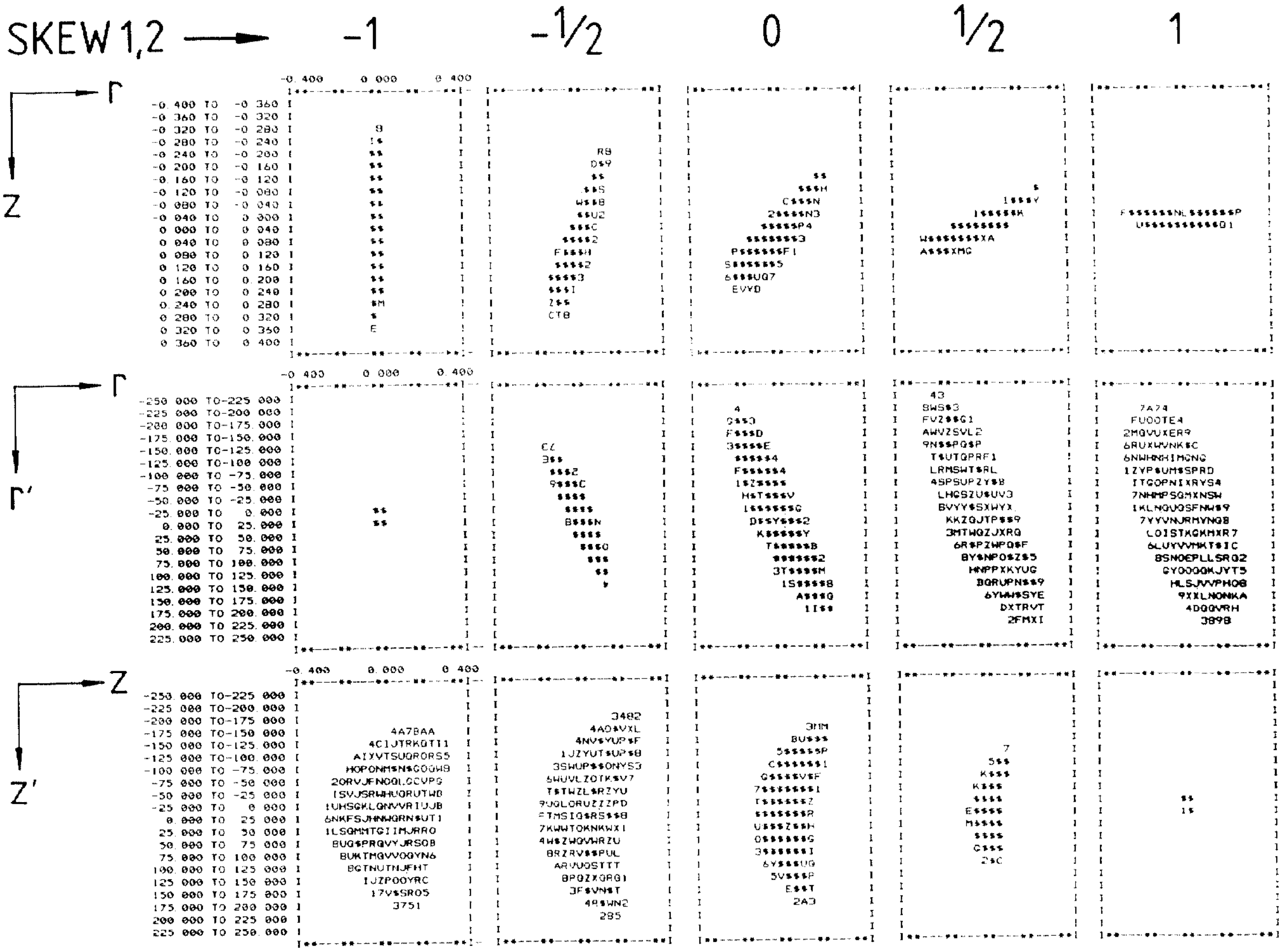

Figure 2:
Beam spot and phase space areas after the hyperbolic inflector in the median plane of JULIC when varying the skew quadrupoles SK1 and SK2 tight together from -1 to +1 in arbitrary units. Frame sizes in the scatter plots are 8 x 8 mm^2 and 8 mm x 500 mrad, respectively.

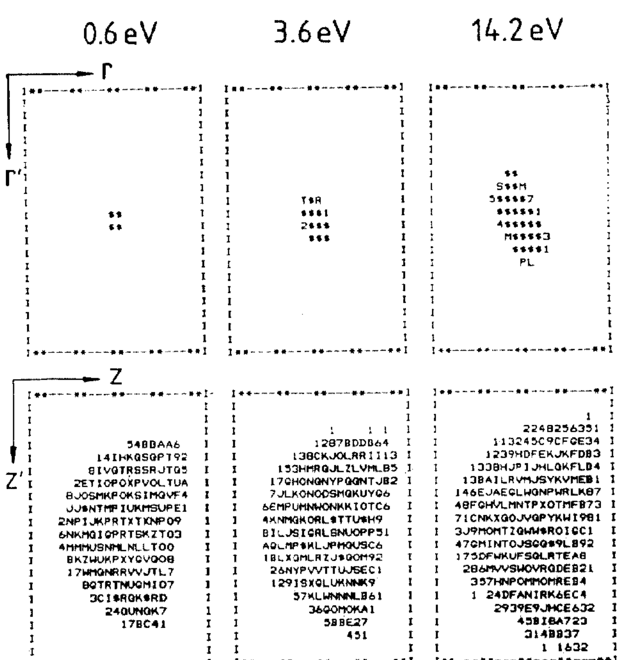

Figure 3:
Phase space areas as in figure 2 for SK1, 2 = -1 when gradually enhancing the transverse ion temperature.

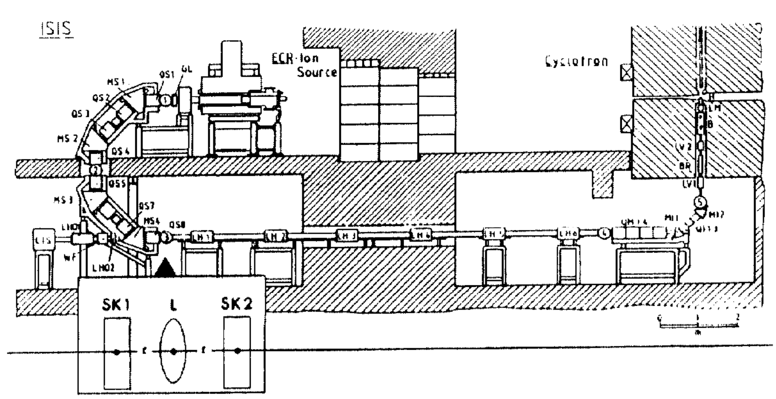

Figure 1:
Beam decorrelation for the ISIS-ECR-source at JULIC consisting of two skew quadrupoles SK1 and SK2 each at the focal distance of a spherical lens L fed into the ISIS-beam guiding system for demonstration purposes. 2f = 0.5 m has been chosen for feasible compactness.