PARTIAL BEAM DECORRELATION OF SOURCES PROVIDING IONS OUT OF AXIAL MAGNETIC FIELDS

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Abstract: The emittance of sources providing ions out of an axial magnetic field can be predicted from analytical theory. If the ion temperature is low the emittance is determined by the strength of the magnetic field, but there is a strong coupling between the horizontal and the vertical phase space. Theory, numerical calculations and experiments with the ISIS-system at JULIC show that the coupling can be partly disentangled in a beam guiding system. Doing this the emittance in one plane can be reduced to the one due to the ion temperature.

Introduction

Almost 20 years ago G.G. Ohlson et al. [1] have described the emittance degradation effect which is associated with the beam formation in an axial magnetic field of a polarized ion source. This article deals with the related beam correlation and the partial beam decorrelation in a beam guiding system. Although these effects are demonstrated using an ECR-ion source the drawn conclusions are as well valid for other sources providing ions out of axial magnetic fields as ground state atomic beam sources for polarized positive ions using strong field ionizers or for negative polarized ions using charge exchange solenoids.

Beam Emittance and Correlation

By an appropriate treatment of the ion motion in a cylindrically symmetric field using the Hamiltonian formalism it has been shown [2,3] that the ray vector of particles leaving the puller region of an ECR-source is given by

$$\begin{pmatrix} x_i \\ \pi_{x_i} \\ y_i \\ \pi_{y_i} \end{pmatrix} = \begin{pmatrix} x_i \\ -y_{i/2R} \\ y_i \\ x_{i/2R} \end{pmatrix}$$

π_{x_i}, π_{y_i} are the canonical momenta which outside the magnetic field are equal to the normal divergencies $1/R = \frac{eB(z)}{P_0}$ is the curvature of ions in the axial magnetic field $B(z)$. Due to this ray vector the emittances of an ECR-source with a circular opening of radius r are given by

$$\epsilon_x = \epsilon_y = \frac{\pi \cdot r^2}{2R}$$

For a numerical example with $r = 4$ mm, $R = 50$ mm $\epsilon = 500$ mm mrad.

If the ion temperature in the source is of the order of 1 eV one may estimate that the lateral divergencies are of the order of 10 mrad for beam energies above several keV. The emittance due to the ion temperature alone would then be

$$\epsilon_T \approx \pi \cdot 4 \cdot 10 \text{ mm mrad} \approx 120 \text{ mm mrad.}$$

Thus one may conclude that the emittance is mainly determined by the magnetic field.

Looking at the initial ray vector one observes that it describes a two dimensional plane in a four dimensional phase space. The emittances which we measure are projections of this plane on our experimental phase planes. To each point in one phase plane belongs one point in the other one (see fig. 1).

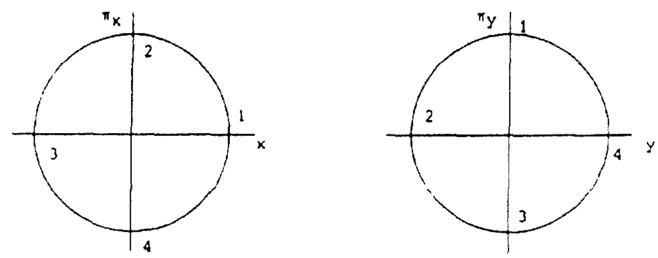

Figure 1:
The correlation in phase space. Point i in the $x\pi_x$-plane corresponds with point i in the $y\pi_y$-plane.

Beam Decorrelation with a Skew Quadrupole

The objective now should be to find ion optical elements which cause such a rotation of the two dimensional plane that it is parallel to one of the planes. This gives some difficulty unless the beam ends again in an axial magnetic field, but is feasible as well [3].

A rotation such that the plane is at right angles to one of the coordinate axes in the four dimensional space is easily performed. Let us assume that the hole of the ECR-source is imaged with the help of a solenoid lens at a certain position in the field free region. Due to the coupling the beam will have azimuthal velocity components as shown in figure 2.

With the help of a skew quadrupole at the position of the image the azimuthal components in one phase space can be compensated, while it is increased by a factor two in the other phase space (see fig. 3). The skew quadrupole exerts a force in azimuthal direction which changes its sign from one pole to the other. The skew quadrupole is not an essential choice. A normal quadrupole may be taken. But than the same decorrelation occurs in a plane rotated by 45^0.

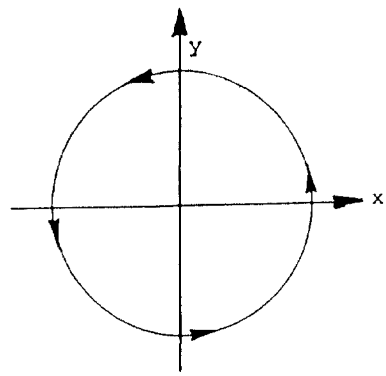

Figure 2:
Azimuthal velocity components due to the coupling between phase spaces.

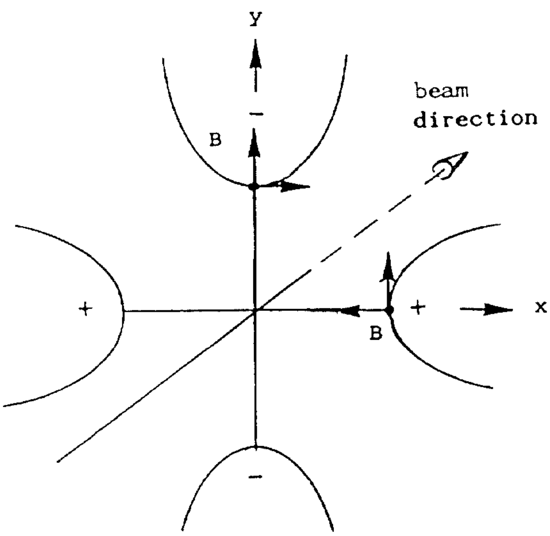

Figure 3:
The effect of a skew quadrupole counter-acting the azimuthal velocity in one plane.

For a discussion of the ion optics using matrix notation we may omit rotational transformations as they only mean some rotation of the coordinate axes which is not essential when looking with a fluorescent target. The ray vector just after the skew quadrupole lens, which is taken as a thin lens, is given by

$$\begin{pmatrix} m_{11}x \\ m_{21}x + (m_{11}S - \frac{m_{22}}{2R})y \\ m_{11}y \\ m_{21}y + (m_{11}S + \frac{m_{22}}{2R})x \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & S & 0 \\ 0 & 0 & 1 & 0 \\ S & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} m_{11} & 0 & 0 & 0 \\ m_{21} & m_{22} & 0 & 0 \\ 0 & 0 & m_{11} & 0 \\ 0 & 0 & m_{21} & m_{22} \end{pmatrix} \begin{pmatrix} x \\ -\frac{y}{2R} \\ y \\ \frac{x}{2R} \end{pmatrix}$$

By setting $S = \frac{m_{22}}{m_{11}2R} = \frac{1}{2m_{11}^2R}$ the correlated part in the x,x' phase plane disappears and the phase space figure has become a straight line with zero emittance. The emittance in the y,y' phase plane has increased by a factor 2:

$$\epsilon_x = 0 \quad \epsilon_y = \pi \cdot m_{11}(m_{11}S + \frac{m_{22}}{2R})r^2 = \frac{\pi \cdot r^2}{R}$$

A set up for observing a partial decorrelation is given in figure 4. The second solenoid is used for making a line focus at the viewer.

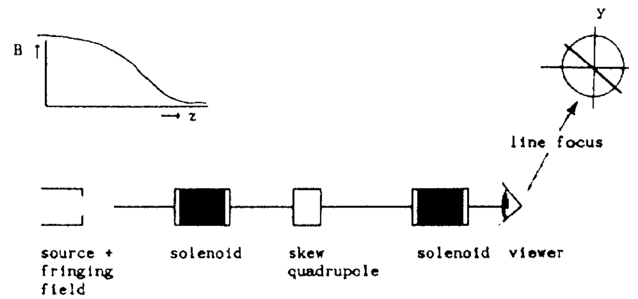

Figure 4:
Set up for observing a partial decorrelation.

Experimental Set-up

The set-up as given in figure 4 happens to be directly available at the ISIS [4] injection system (see figure 5). Using the 5 GHz ECR source (LIS) the solenoid LH01 is taken as imaging lens, the quadrupole QS8, part of the 180° bending system, as compensating quadrupole and the solenoid LH1 as lens to form a line image on a viewing screen. This viewing screen was the only necessary addition to the system. Since we did not want to introduce additional fields the Wienfilter was not used and the experiment was planned and finally performed with a He^+-beam which can be provided from the source rather cleanly.

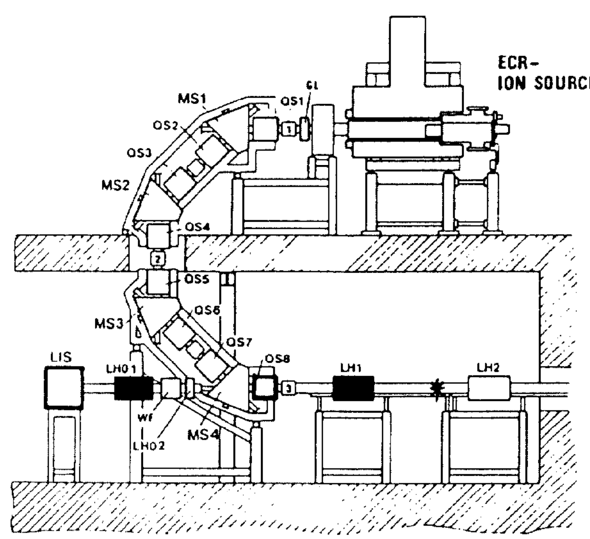

Figure 5:
First part of the layout of the project ISIS:
LIS-light ion source; LH01, LH1-solenoid lenses, QS8-quadrupole magnet; *-location of the viewing screen.

Ray Tracing Calculation

Prior to the experiments calculations with the codes TRANSPORT [5] and TURTLE [6] have been performed to check the formulations in thin lens approximation and to find appropriate settings of the real lenses for the experiment. The beam correlation was introduced appropriately using the input feature for an arbitrary matrix in TRANSPORT and TURTLE.

The partial decorrelation as well as the line at the viewing screen can be found in a single TRANSPORT run fitting for zero beam extent in one direction in an arbitrarily rotated coordinate system.

The lens settings obtained by this procedure have been used in TURTLE runs to visualize the results. Figure 6 shows histograms in the x,y-coordinate system at the viewer location. The effect of partial decorrelation becomes clear if one compares the line of no extent in the middle histogram with the big spot which would occur in case there would be no correlation built into the beam at the ion source. The remark - beam correlation off - means that an uncorrelatedly filled emittance of 600 mm mrad comes into picture.

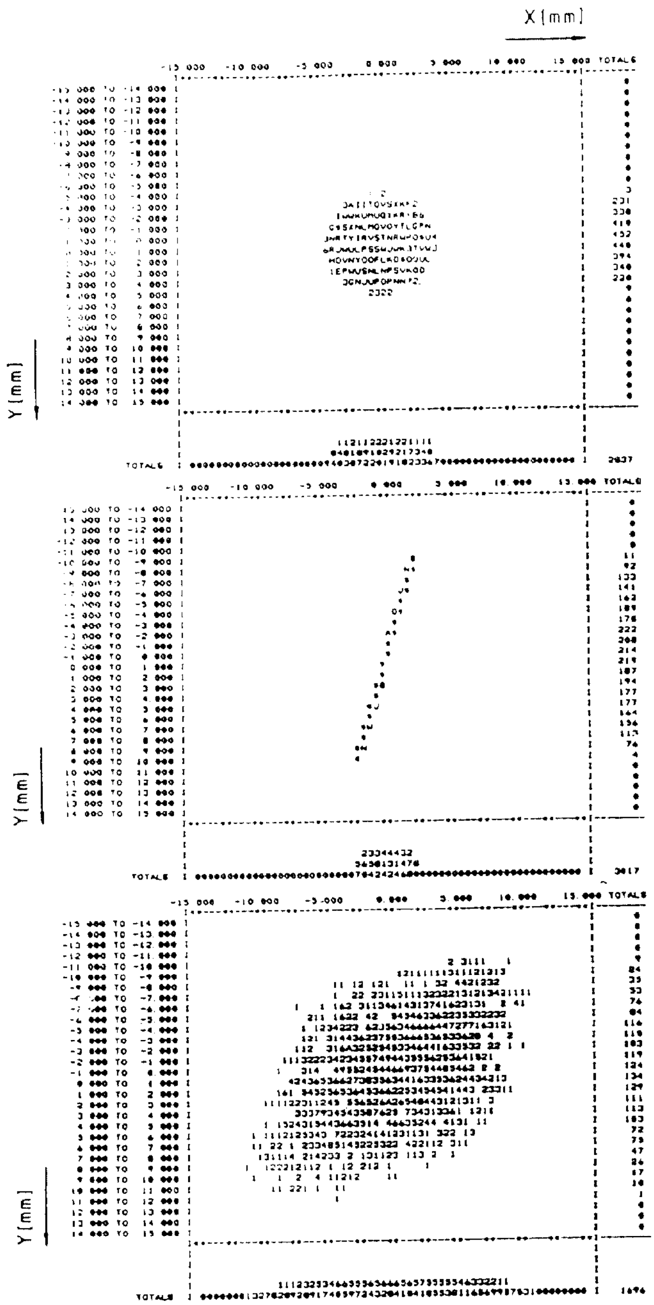

Figure 6:
x,y-histograms for 10.000 starting rays at the viewer location
top: beam correlation on, quadrupole off
middle: beam correlation on, quadrupole on
bottom: beam correlation off, quadrupole on

Experimental Result

The experimental result is shown in figure 7 displaying a photograph of the line at the viewing screen. For half the exposure time the quadrupole was on positive the other half on negative setting.

Figure 7:
Photograph of the lines at the viewing screen.

Only the setting of the lens LH01 had to be tuned differently compared to the settings used in the TURTLE runs of figure 6. Although the fringe field of the ECR source was included in the TURTLE runs using an appropriate set of solenoids the program is not able to simulate the real ion optics coming from the plasma surface and the electric fields in the puller gap including space charge. Even though only little time was spent on the experiment so far it was evident that heavy and fluctuating changes in the line at the viewer occurred when the microwave power to the plasma was changed or a change in the gas flow led to different currents out of the source.

Conclusion

It has been shown that the beam correlation due to the passage of ions through the falling axial magnetic field exists and that decorrelation techniques work. Even though possible applications of the partial decorrelation [3] have to be further developed and realized it is quite clear that it can be used as a diagnosis tool for ECR- and other sources providing ions out of an axial magnetic field.

References

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