TRANSVERSE COUPLING OF ION BEAMS FROM AN RCR ION SOURCE

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Abstract

Transverse coupling of ion beams out of an ECR ion source has been studied from two aspects. One is the coupling induced during beam extraction and the other is the coupling effect of a solenoid. Ion beams extracted from an electron cyclotron resonance (ECR) ion source will experience a descending axial magnetic field at the extraction region, resulting in a strong transverse coupling to the extracted beam, with projection root-mean-square (RMS) emittance growth both in horizontal and vertical directions and two eigen-emittances separation. Simulations of particle beam extraction from an ECR ion source in the present of the magnetic field have been carried out to investigate the coupling property. The results indicate the magnetic field in the extraction region can determine the beam emittances and the transverse coupling by affecting the beam formation. In addition, coupling effect of a solenoid on an initially non-round beam has been illustrated by introducing the matrix algorithm, which can qualitatively and indirectly explain the experimental phenomenon of SECRAL (Superconducting Electron Cyclotron Resonance ion source with Advance design in Lanzhou) at institute of modern physics (IMP).

INTRODUCTION

As one of the most powerful devices to produce intense highly-charged heavy ion beams, ECR ion sources are widely adopted by many large accelerator facilities. However, because of its special magnetic confinement fields ECR ion source beam quality has always been concerned and achieved much attention. Since the extraction of the ions takes place in the vicinity of a local magnetic field maximum, the following descending axial magnetic field adds an azimuthal momentum to the beam, leading to the transverse emittances blow up and coupling. It is generally believed that the beam emittance is primarily determined by the axial field strength at the extraction region if the ion temperature in the ECR plasma is low [1, 2]. The magnetic contribution to the (Normalized RMS) emittance can be given by

$$\varepsilon_{mag} = 0.032 \cdot (R_{extr})^2 \cdot (\frac{B_{extr}}{M/Q}), \quad (1)$$

where R_{extr} [mm] is the radius of the effective extraction aperture and M/Q the ion mass-to-charge ratio and B_{extr} [T] the maximum magnetic field at the extraction region. This equation indicates the beam projection emittance is proportional to the extraction field strength. However, beam emittance measurements for the ECR ion source at RIKEN with a pepper-pot scanner do not have a good agreement with the accepted theorem as described above [3, 4]. In their experiment both the projection RMS emittances and the 4-D emittance are lower under a relatively larger B_{extr}, which indicates a more complicated extraction process. Besides the coupling induced by the semi-solenoid field in the ion source extraction region, a complete solenoid, which is usually employed as the initial focusing element, can also lead to beam coupling since the ion density distribution across the extraction aperture is inhomogeneous due to the asymmetric plasma distribution at extraction, resulting in a non-round beam [5].

This paper starts with an introduction of the relationship between the projection RMS emittances and eigen-emittances based on modeling a beam passing through a semi-solenoid field. Afterwards beam extraction simulations are carried out toward SECRAL [6] to investigate the transverse coupling property of the extracted beam. Then coupling effect of a solenoid field on a non-round beam is demonstrated by analytical theory in combination with the experimental results with SECRAL. The last section makes some conclusions and an outlook.

BASIC THEOREM

Beam RMS emittances are defined through the beam second moment matrix [7, 8]

$$C = \begin{bmatrix} <xx> & <xx'> & <xy> & <xy'> \\ <x'x> & <x'x'> & <x'y> & <x'y'> \\ <yx> & <yx'> & <yy> & <yy'> \\ <y'x> & <y'x'> & <y'y> & <y'y'> \end{bmatrix}, \quad (2)$$

where the full 4-D emittance is defined by

$$\varepsilon_{4d} = \sqrt{\det(C)}\,. \quad (3)$$

The projection RMS emittances ε_x and ε_y are defined by the corresponding sub phase space determinants, which can completely characterize the transverse quality when the beam is transversely uncoupled. Diagonalization of the beam matrix yields the eigen-emittances ε_1 and ε_2, whose values can be expressed as:

$$\varepsilon_{1,2} = \frac{1}{2}\sqrt{-tr[(CJ)^2] \pm \sqrt{tr^2[(CJ)^2] - 16\det(C)}}\,. \quad (4)$$

The 4-D matrix J is the skew-symmetric matrix with non-zero entries on the block diagonal off form. A symplectic transformation M obeys

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$$M^T JM = J\,,\quad J = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \end{bmatrix}. \tag{5}$$

Drifts, solenoids, quadrupoles, and dipoles are all symplectic, through which transformations beam eigen-emittances are invariant. Coupling between horizontal and vertical planes results in

$$\varepsilon_{4d} = \varepsilon_1 \cdot \varepsilon_2 \le \varepsilon_x \cdot \varepsilon_y \tag{6}$$

with equality just for zero inter-plane coupling moments.

The extraction aperture of most ECR ion sources is located near the center of the extraction solenoid coil [6], therefore particles are extracted and accelerated in a semi-solenoid magnetic field, which provides a non-symplectic transformation R_{out}. For simplicity, assuming a very short solenoid, its transfer matrix in the exit fringe can be described by:

$$R_{out} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & -\kappa & 0 \\ 0 & 0 & 1 & 0 \\ \kappa & 0 & 0 & 1 \end{bmatrix}, \tag{7}$$

where

$$\kappa = \frac{B_{extr}}{2(B\rho)}. \tag{8}$$

B_{extr} is the solenoid on-axis magnetic field strength, and $(B\rho)$ is the particle rigidity. Assuming the initial beam out of the ion source extraction hole has equal horizontal and vertical RMS emittances and no inter-plane correlations, the beam matrix can be simplified to (in the case here, assuming Twiss parameters $\alpha_{x,y}$=0)

$$C_0 = \begin{bmatrix} \varepsilon\beta & 0 & 0 & 0 \\ 0 & \frac{\varepsilon}{\beta} & 0 & 0 \\ 0 & 0 & \varepsilon\beta & 0 \\ 0 & 0 & 0 & \frac{\varepsilon}{\beta} \end{bmatrix}. \tag{9}$$

When the beam passes through the exit fringe of the solenoid, the beam matrix C_1 is found as

$$C_1 = R_{out} C_0 R_{out}^T = \begin{bmatrix} \varepsilon\beta & 0 & 0 & \kappa\varepsilon\beta \\ 0 & \frac{\varepsilon}{\beta} + \kappa^2\varepsilon\beta & -\kappa\varepsilon\beta & 0 \\ 0 & -k\varepsilon\beta & \varepsilon\beta & 0 \\ \kappa\varepsilon\beta & 0 & 0 & \frac{\varepsilon}{\beta} + \kappa^2\varepsilon\beta \end{bmatrix}. \tag{10}$$

Inter-plane correlations are created in the *xy'* and *x'y* phase spaces and the RMS emittances and eigen-emittances become

$$\varepsilon_x = \varepsilon_y = \sqrt{\varepsilon\beta(\frac{\varepsilon}{\beta} + \kappa^2\varepsilon\beta)}\,, \tag{11}$$

$$\varepsilon_{1,2} = \varepsilon_x \pm \kappa\varepsilon\beta\,. \tag{12}$$

It can be seen that both the RMS emittances ε_x and ε_y have a significant growth and the two eigen-emittances separate, nevertheless, the 4-D emittance preserves.

The realistic semi-solenoid field has a certain integral length, whose transmission matrix can be read as

$$R_{out} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & -\kappa & 0 \\ 0 & 0 & 1 & 0 \\ \kappa & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & \frac{\sin(\kappa L)}{2\kappa} & 0 & \frac{\sin(\kappa L/2)^2}{\kappa} \\ 0 & \cos(\kappa L) & 0 & \sin(\kappa L) \\ 0 & -\frac{\sin(\kappa L/2)^2}{\kappa} & 1 & \frac{\sin(\kappa L)}{2\kappa} \\ 0 & -\sin(\kappa L) & 0 & \cos(\kappa L) \end{bmatrix}, \tag{13}$$

where L is the integral length of the whole extraction solenoid of the ion source.

BEAM EXTRACTION SIMULATION THROUGH A SEMI-SOLENOID FIELD

The magnetic confinement fields of an ECR ion source are typically achieved by the superposition of an axial mirror field and a radial sextupole field, resulting in

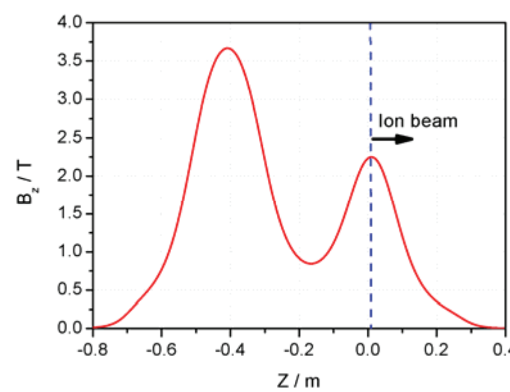

Figure 1: Axial magnetic field distribution of SECRAL.

ISBN 978-3-95450-186-1

a so called minimum-B field configuration. Fig.1 shows the axial magnetic field distribution of SECRAL. The plasma electrode is located in the vicinity of the extraction mirror peak, leading to extraction of ions from a strong magnetic field and subsequent beam formation in decaying fringe field. Extraction simulation in this section will mainly focus on the contribution of the magnetic field to the beam emittance.

The ion beam extraction has been modeled with the ion optical code IBSimu [9, 10, 11]. In the simulation, ions are extracted from plasma that is modeled in a reduced volume. The 3-D magnetic field map, which includes the solenoid and hexapole fields, is calculated with TOSCA and read by the code. The first simulation is aimed at a $^{129}Xe^{29+}$ beam with extraction voltage of 25 kV. Fig. 2 illustrates the simulated ion trajectory densities through the extraction region with three different field strengths of B_{extr}=1.35 T, B_{extr}=2.03 T and B_{extr}=2.7 T. Fig. 3 presents the beam emittances (including the projection RMS emittances ε_x and ε_y and eigen-emittances ε_1 and ε_2) and the corresponding products $\varepsilon_x*\varepsilon_y$ and $\varepsilon_1*\varepsilon_2$ along the extraction path when the B_{extr}=1.35 T. Simulation results agree well with the theoretical prediction that the two eigen-emittances tend to heavily separate, with one value increasing and the other decreasing, but both projection emittances rise up in the strong magnetic field. Finally the difference between ε_1 and ε_2 reaches several hundred times at the end of the extraction region (z=0.38 m), and the value of $\varepsilon_{x,y}$ becomes nearly ten times larger than that at the point of z=0.05 m where the accelerating process is almost accomplished. The 4-D emittance, which is equal to $\varepsilon_1*\varepsilon_2$, keeps constant, but the value of $\varepsilon_x*\varepsilon_y$ has a significant growth.

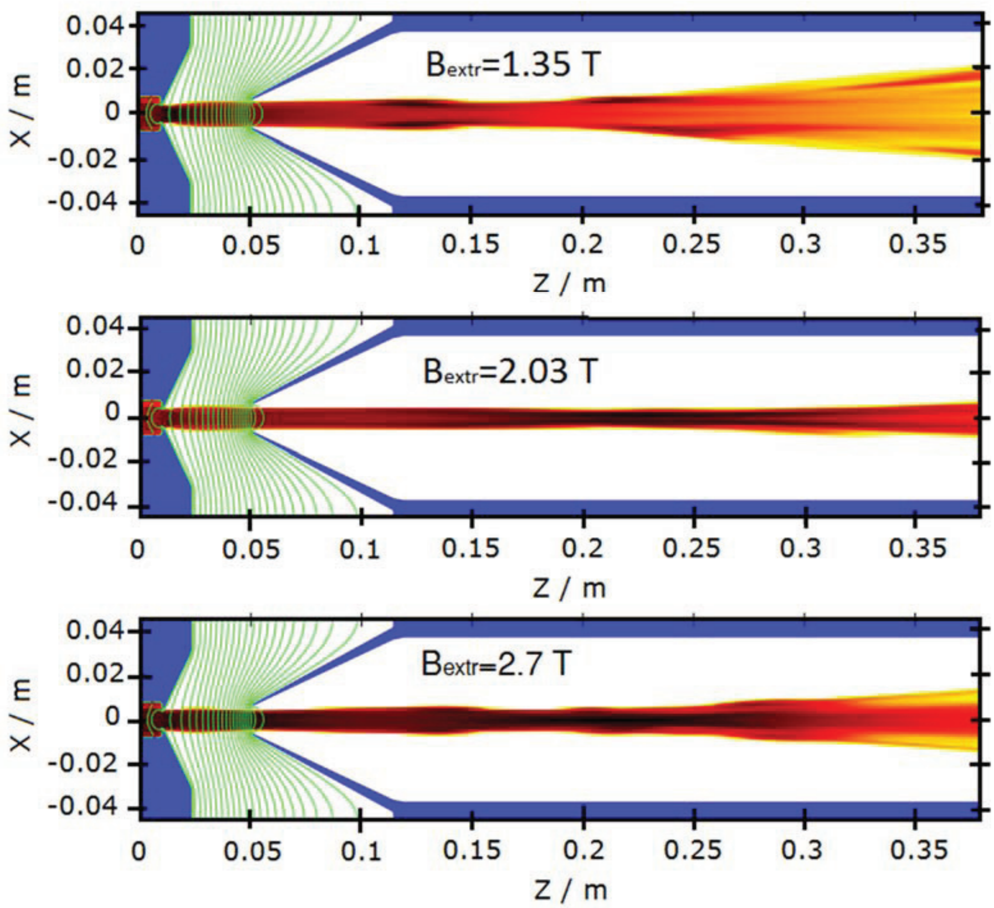

Figure 2: Simulated ion trajectory densities through the extraction region with B_{extr}= 1.35 T, B_{extr}=2.03 T and B_{extr}=2.7 T.

To investigate the effect of the magnetic field in the extraction region simulations with different amplitudes of B_{extr} are performed. Fig. 4 shows the simulated beam emittances and the corresponding products versus B_{extr} at the end of the extraction region (z=0.38 m), in which the expected emittance calculated according to formula (1) is also given (with R_{extr}=5 mm). It is clear the projection emittances do not increase with the magnetic field strength proportionally as predicted by formula (1), but there exist an optimal field (B_{extr}=2.03 T) under which condition the projection emittance $\varepsilon_{x,y}$ reaches minimum and the value of $\varepsilon_x*\varepsilon_y$ is closest to $\varepsilon_1*\varepsilon_2$, and also, the difference between the two eigen-emittances ε_1 and ε_2 is smallest. It means under this condition the coupling in the

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transverse phase space is relatively weak. 4-D matrices (in units of mm and mrad) of the beams at the end of the extraction region in the cases of B_{extr}=1.35 T, B_{extr}=2.03 T and B_{extr}=2.7 T are

$$C_{1.35\,T}=\begin{bmatrix} 105.9975 & 476.0413 & -0.2120779 & -196.2880 \\ 476.0413 & 2466.011 & 175.0482 & -81.79913 \\ -0.2120779 & 175.0482 & 95.20618 & 432.9456 \\ -196.2880 & -81.79913 & 432.9456 & 2330.547 \end{bmatrix}, \quad (14)$$

$$C_{2.03\,T}=\begin{bmatrix} 13.14704 & 70.28109 & -0.4886135 & -37.11058 \\ 70.28109 & 468.760 & 29.29614 & -22.68711 \\ -0.4886135 & 29.29614 & 11.82261 & 66.22893 \\ -37.11058 & -22.68711 & 66.22893 & 468.3700 \end{bmatrix}, \quad (15)$$

and

$$C_{2.7\,T}=\begin{bmatrix} 44.9443 & 238.4365 & -1.350854 & -101.0213 \\ 238.4365 & 1465.950 & 87.37357 & -27.78315 \\ -1.350854 & 87.37357 & 44.73177 & 243.2753 \\ -101.0213 & -27.78315 & 243.2753 & 1519.878 \end{bmatrix} \quad (16)$$

respectively. It is clear that when B_{extr}=2.03 T the absolute values of the off-diagonal sub-matrix elements are much lower than those with B_{extr}=1.36 T or B_{extr}=2.7 T except for the infinitesimal <*xy*>.

The cause of this non-proportional relationship between the beam emittance and the magnetic field strength is that the magnetic field plays an important role in the beam formation in the extraction region, with the transverse coupling changed. The extracted beam profiles with B_{extr}=1.35 T, 2.03 T and 2.7 T are compared in Fig. 2. It is found that the plasma meniscuses under different magnetic fields have the same shapes, however, the magnetic field with strength of 2.03 T, together with the electric field in the acceleration gap, provide a proper focusing effect, resulting in a quasi-parallel beam with a small divergence as well as a small envelope inside the grounded electrode. While in the case of B_{extr}=1.36 T the beam is less focused, but over focused in the field of 2.7 T. According to equation (11) and (12) derived from the simplified semi-solenoid model, for a given particle rigidity, the beam emittances (including the projection emittances and eigen-emittances) out of a exit fringe field are related not only to the field strength B_{extr} but also to the initial beam emittance ε and beam size (equal to $2\sqrt{\varepsilon\beta}$). In another words, besides adding an azimuthal momentum to the beam, the magnetic field can also determine the beam emittances and the transverse coupling by affecting the beam formation in the extraction region. This can be a possible reason of the experimental phenomenon that the beam emittance with lower B_{ext} is larger than that with higher B_{ext} for RIKEN ECR ion source [3, 4].

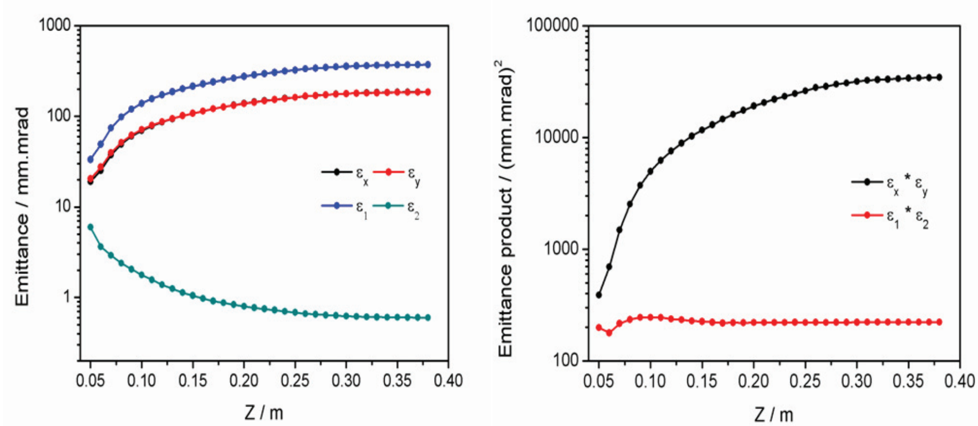

Figure 3: Beam emittances and the corresponding products ε_x*ε_y and ε_1*ε_2 along the extraction path when B_{extr}=1.35 T.

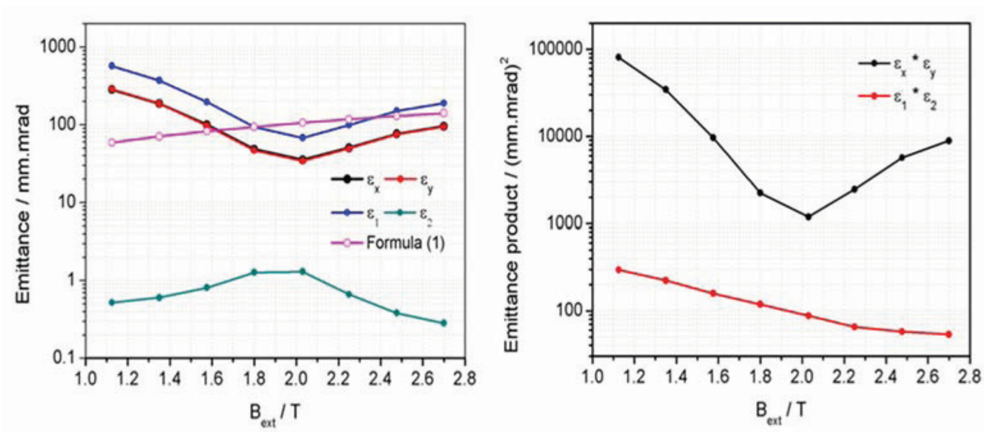

Figure 4: Beam emittances and the corresponding products versus B_{extr}.

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According to the simulations, it is of interest to realize that the 4-D emittance decreases with increasing the extraction magnetic field strength. Since the 4-D emittance keeps constant after accelerating, it is easy to imagine that the magnetic field in the acceleration gap is one of the decisive factors of the 4-D emittance. By observing the beam extraction profiles in Fig. 2, we can find the main reason is that the beam size at the location of the grounded electrode is focused to be smaller with a larger magnetic field, which helps to avoid the large-radius aberration in the einzel lens and improve the beam quality.

COUPLING EFFECT OF A SOLENOID

In the previous section, we have discussed the transverse coupling resulting from the non-conservation of the angular momentum of the beam out of a semi-solenoid field. However, a complete solenoid can also induce beam coupling if it is a non-round beam, although through which beam's angular momentum keeps constant. Our experimental results have indicated that the cross section of extracted beam from ECR is not round along transport path [12]. The experiment is based on the measurement of the projection emittance (for $^{129}Xe^{29+}$ with the extraction voltage of 25 kV) with SECRAL by changing the field strength and the polarity of the solenoid lens which is installed just after the source body. Experimental result is presented in Fig. 5, in which "F" means forward current being loaded on the solenoid, in which case the beam transmits in the direction of the solenoid lens axial field in the beam pipe, while "R" means the polarity of the solenoid lens is reversed. This plot indicates that the emittances tend to transfer between the two orthogonal directions as the solenoid current is increased and in addition, allot values dramatically differ in the two directions when reversing the polarity of the solenoid field. The maximum difference between the two projection emittances can even reach several times. The change of the emittance values with the solenoid current can be due to the fact that the ion beam extracted from the ECR ion source is not round and can produce periodic coupling in a solenoid which has a rotation effect to the beam.

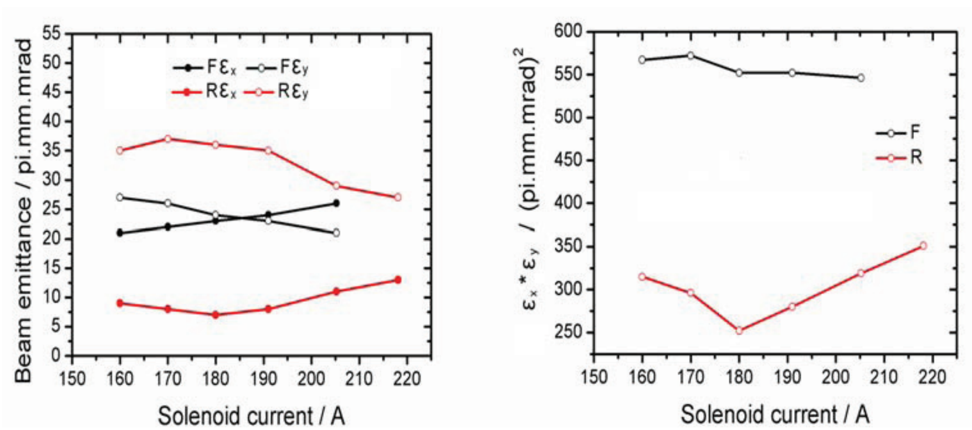

Figure 5: Measured beam emittances and the corresponding product by changing the focusing strength and reversing the polarity of the beam line solenoid.

In order to illustrate the coupling effect of a solenoid on a non-round beam and explain the experimental phenomenon indirectly and qualitatively, matrix algorithm is applied. Firstly, we make an artificial beam matrix with zero inter-plane elements as

$$C = \begin{bmatrix} 10 & 65 & 0 & 0 \\ 65 & 485 & 0 & 0 \\ 0 & 0 & 10 & 65 \\ 0 & 0 & 65 & 432.5 \end{bmatrix}, \qquad (17)$$

which has the same envelope in the two projected directions but different emittances, with ε_x=25 mm.mrad and ε_y=10 mm.mrad. Let this beam pass through a solenoid with effective length of L_{eff}=0.18 m, the beam emittances and their products versus the solenoid field are calculated and plotted in Fig. 6 for a particle rigidity of 0.0479 Tm (for $^{129}Xe^{29+}$ with extraction voltage of 25 kV). It is clear that the beam coupling in the transverse phase space has a periodic property, resulting in a periodic change both in the projection emittance and the corresponding product as the field strength of the solenoid is changed. When the value of the projection emittance product ε_x*ε_y reaches minimum, equal to the eigen-emittance product ε_1*ε_2, the coupling is removed.

Besides its focusing effect, a solenoid can bring a phase space rotation to the beam. The rotation angle is

$$\Theta = \kappa L_{eff} = \frac{B_{max}}{2(B\rho)} L_{eff}, \qquad (18)$$

where B_{max} is the on-axis magnetic field strength. When $\Theta = n \cdot \frac{\pi}{2}$, $n = 0, \pm 1, \pm 2, \pm 3, \cdots$, the beam is uncoupled, in which the horizontal and vertical planes exchange if $n = \pm 1, \pm 3, \pm 5, \cdots$.

The second artificial beam matrix is assumed as

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$$C = \begin{bmatrix} 10 & 65 & 0 & 0 \\ 65 & 485 & 0 & 0 \\ 0 & 0 & 20 & 65 \\ 0 & 0 & 65 & 242.5 \end{bmatrix}, \quad (19)$$

which has equal projection emittances, but different sizes in the horizontal and vertical planes. For this case, a solenoid can also create periodic coupling due to the rotation effect, although the two projection emittances are always equal to each other, as shown in Fig. 7.

For the case that a beam has both unequal emittances and sizes in the two projected directions, with an assumed matrix of

$$C = \begin{bmatrix} 10 & 65 & 0 & 0 \\ 65 & 485 & 0 & 0 \\ 0 & 0 & 20 & 65 \\ 0 & 0 & 65 & 216.25 \end{bmatrix}, \quad (20)$$

the coupling effect of a solenoid is presented by Fig. 8. It is noteworthy that for this case the coupling is much stronger than that in the first and second cases by comparing the value of ε_x*ε_y.

In a word, the rotation effect of a solenoid field could bring a periodic coupling to a non-round beam, even though it is initially uncoupled. With regard to the experimental result with SECRAL (as shown in Fig. 5), when the solenoid current is -180 A, the value of ε_x*ε_y reaches minimum and the beam quality is optimal. That is because under this condition the solenoid (after the ion source) disentangles the coupling by compensating the beam rotation (not rotational momentum) caused by the semi-solenoid field in the extraction region on the premise of initially non-round beam. However, the coupling is not completely removed unless in an opposite magnetic field of the same the particles experienced while they were extracted or by using a skew quadrupole (or a skew triplet) [7, 8].

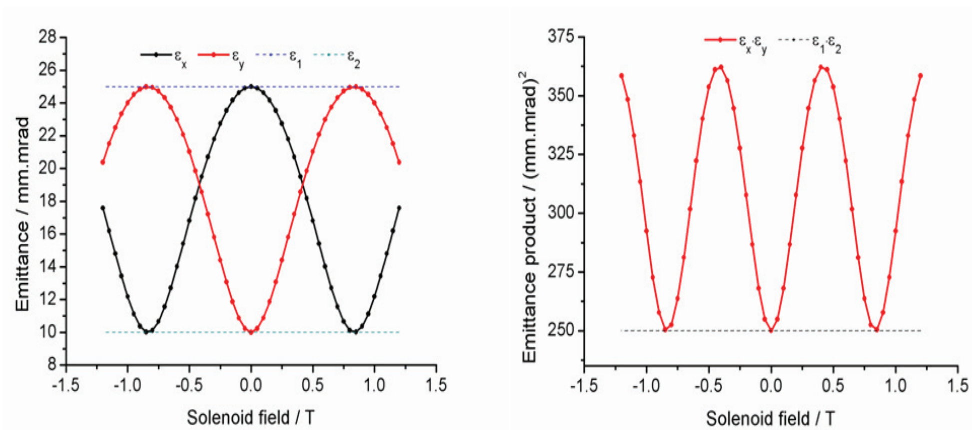

Figure 6: Calculated beam emittances and their products versus the solenoid field for the first case.

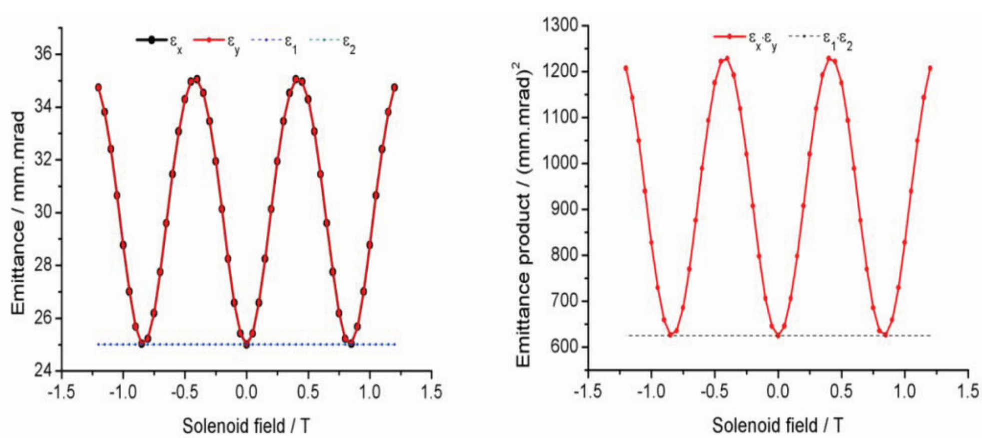

Figure 7: Calculated beam emittances and their products versus the solenoid field for the second case.

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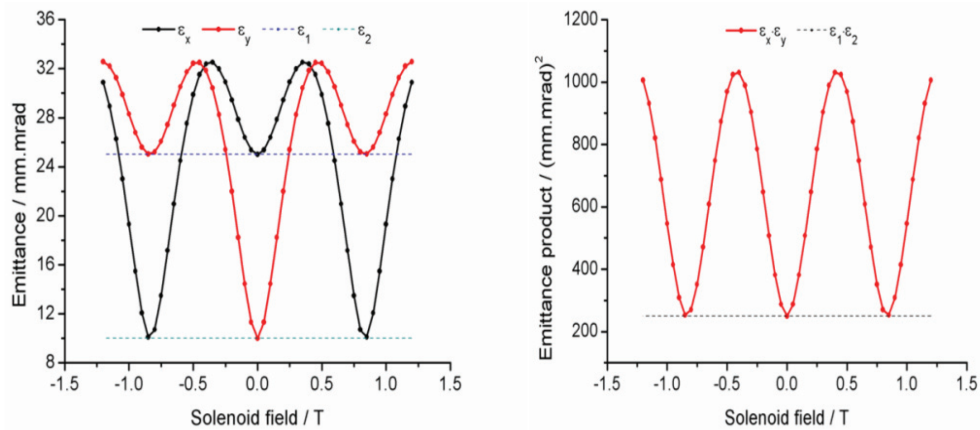

Figure 8: Calculated beam emittances and their products versus the solenoid field for the third case.

CONCLUSION AND OUTLOOK

Transverse coupling of ion beams out of an ECR ion source has been studied from two aspects. One is the coupling induced during beam extraction and the other is the coupling effect of a solenoid. Particle beam extraction from an ECR ion source in the present of magnetic fields has been modeled. A strong coupling in the transverse space is established through the semi-solenoid field in the extraction region, resulting in the projection emittance growth both in horizontal and vertical and the two eigen-emittances separation. Simulations do not show a proportional increasing of the projection emittances with scaling up the extraction field strength, but there exist an optimal field under which condition the coupling is weakest with the projection emittance reaching minimum. The cause of this phenomenon is that the magnetic field takes effect on the beam formation in the extraction region, with the transverse coupling changed. An interesting phenomenon presented in the simulation is that the 4-D emittance decreases with increasing the extraction magnetic field strength, which can be attributed mainly to the fact that the beam size at the location of the grounded electrode is focused to be smaller with a larger magnetic field, helping to avoid the large-radius aberration in the einzel lens and improve the beam quality. In actual adjustment of the extraction magnetic field, it is not used primarily to optimize the extracted beam formation, but to optimize the plasma confinement. Therefore, in order to achieve a high-quality beam, we should optimize the plasma conditions and the electric field in the acceleration gap (by using a moveable extraction electrode) by combination with the local magnetic field to optimize the beam profile. On the other hand, coupling effect on an initially non-round beam due to the rotation function of a solenoid has been demonstrated by introducing the matrix algorithm, which can qualitatively and indirectly explain the experimental phenomenon of SECRAL. However, the fly in the ointment is that the beam extraction simulations do not reflect a non-round beam due to the limited modeling in the ECR plasma distribution. To obtain more comprehensive qualities of ion beams from an ECR, measurements using a pepper-pot scanner are very essential, which is now under development at our institute.

ACCKNOWLEGEMENTS

This work is supported by the National Nature Science Foundation of China (contract No.11405238 and 11575265) and 973 Research program 2014CB845500.

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ISBN 978-3-95450-186-1