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## Transmission efficiency improvement of the injector line of SFC by particle beam decorrelation postprint

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### Abstract

The operation of the HIRFL accelerator has shown that the beam transmission efficiency of the sector focusing cyclotron (SFC) injector line is rather poor. Beam simulations have been performed to investigate the possible causes for this low transmission. It is predicted that the property of transversal coupling of the ion beam from electron cyclotron resonance (ECR) ion source can be an important factor to degrade the beam quality by increasing the beam emittance, resulting in a serious particle loss. An improved operation scheme for the SECRA associated line has been proposed, and the corresponding experiment was carried out. This paper presents the test results.

### Full Text

### Preamble

#### Transmission Efficiency Improvement of the Injector Line of SFC by Particle Beam Decorrelation

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The operation of the HIRFL accelerator has shown that the beam transmission efficiency of the sector focusing cyclotron (SFC) injector line is rather poor. Beam simulations have been performed to investigate the possible causes for this low transmission. It is predicted that the transverse coupling property of the ion beam from the electron cyclotron resonance (ECR) ion source can be an important factor that degrades beam quality by increasing the beam emittance, resulting in serious particle loss. An improved operation scheme for the SECRAL associated line has been proposed, and the corresponding experiment was carried out. This paper presents the test results.

**Keywords:** Electron cyclotron resonance, Emittance, Transverse, Coupling  
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## Introduction

The Heavy Ion Research Facility at Lanzhou (HIRFL) [?, ?] consists of four accelerators in series: a sector focusing cyclotron (SFC), a separator sector cyclotron (SSC), a cooling storage synchrotron (CSRm), and a cooling storage synchrotron for experiments (CSRe). The SFC serves as the injector for the SSC and also as an injector for the CSRm for light ions (SFC+CSRm mode), while the SFC and SSC work together to inject heavy ions into the CSRm (SFC+SSC+CSRm mode).

Three ion sources currently serve the HIRFL: LAPECR1 (Lanzhou All Permanent magnet Electron Cyclotron Resonance ion source No.1), LECR3 (Lanzhou Electron Cyclotron Resonance ion source No.3), and SECRAL (Superconducting Electron Cyclotron Resonance ion source with Advanced design in Lanzhou) [?]. SECRAL is a fully superconducting electron cyclotron resonance (ECR) ion source dedicated to highly charged heavy ion beam production.

Operation of the SECRAL ion source has demonstrated outstanding performance in terms of high beam intensity. However, routine operation of the accelerator shows that the beam transmission efficiency of the injector line from SECRAL to the SFC is only around 50%. Various hypotheses have been proposed to explain this low transmission, mostly focusing on buncher efficiency and alignment problems, though without much convincing evidence so far.

Recently, research on the transverse coupling property of ion beams from ECR ion sources has been carried out [?]. It is predicted that this property can be an important factor causing projection transverse emittance blowup, as the beam coupling is intensified by the solenoid lenses in the SECRAL associated line. An improved operation scheme for the SECRAL associated line was proposed based on beam simulations: adjust the solenoid lenses to achieve a transversely decoupled beam so that the projection transverse emittances reach minimum values. The experiment to verify this proposal indicates that by using this operation scheme, the beam transmission efficiency of the SFC injector line can be increased to 75%. However, for high-intensity ion beams, the existing optical elements are incapable of creating a decoupled beam due to beam focusing

requirements. A modification proposal for the Q/A selector system of SECRAL is presented, and its reasonability and feasibility are proven through simulations.

## II. The Injector Line of SFC

[Figure 1: see original paper] shows the layout of the SFC injector line. It consists of three sections: the SECRAL associated line, the proton and medium-mass ion beam line shared by LAPECR1 and LECR3, and the vertical line to reach the SFC. The vertical line is mainly composed of five magnetic quadrupoles (Q1–Q5), three solenoids before the SFC entrance, two longitudinal bunchers, and one chopper (not shown). A dual-90-degree bending magnet BM4 serves as the transmission link to deliver ion beams from ground level, where the ion sources are located, to the vertical line.

The SECRAL associated line (from the ion source exit to BM4) includes three solenoid lenses (SN1, SN2, and SN3), three bending magnets (BM1, BM2, and BM3), and two testing chambers. After extraction from SECRAL, ion beams are initially focused by SN1. The desired ion species are selected by BM1, a double-focusing  $110^\circ$  analyzing magnet. Following BM1 is a test chamber where a Faraday cup (FC1), a fluorescent target, and an Allison-type emittance measuring device (EMD) are placed. Because BM4 is below the level of SECRAL, two identical  $45^\circ$  bending magnets (BM2 and BM3) are introduced to bend the beam vertically to reach BM4. Two identical solenoids, SN2 and SN3, are installed on each side of the dual-bending magnets to provide focusing forces to the beam. Another test chamber, equipped with only a Faraday cup (FC2), is located behind SN3.

## III. Particle-in-Cell (PIC) Simulation with a Transverse Coupled Beam from ECR Ion Source

The injection line was initially designed with the Trace-3D program [?]. Figure 2 illustrates a simulated beam envelope for a 25 kV  $^{209}\text{Xe}^{29+}$  beam from the SECRAL exit to the SFC entrance. The cross-section of the beam from the ion source is assumed to be round and axisymmetric, having no correlation between horizontal and vertical projection phase space.

However, for an ECR ion source, the ion density distribution across the extraction aperture is inhomogeneous due to the magnetic confinement fields, resulting in a non-round beam cross-section along the transport path. When ions are extracted and accelerated through the descending axial magnetic field in the extraction region, the horizontal and vertical phase spaces become strongly coupled. Recently, the transverse coupling property of beams from ECR ion sources was studied [?], and the beam coupling configuration was characterized in 4-D phase space at the ion source exit for  $^{209}\text{Xe}^{29+}$  beam under 25 kV extraction voltage.

Due to the periodic property of the coupling, the solenoid lens behind the ion

source (SN1) can periodically disentangle the coupling by changing the focusing strength [?]. To achieve higher transmission efficiency, the ion beam should have minimum projection emittance values both horizontally and vertically; that is, the ion beam should be transversely decoupled. This is because the determinant of the 4-D sigma matrix remains constant for both coupled and decoupled ion beams, but the product of horizontal and vertical projection emittances can only be minimized at the determinant value for decoupled beams. However, the solenoid lens SN1 is mainly used for initial focusing and size control of the beam entering the analyzing magnet and is responsible for tuning flexibility of the Q/A selector system for all ion species produced by the ion source [?]. Therefore, the adjustable range of the solenoid lens current is limited.

To find an optimal operation scheme for the SECRAL associated line, PIC simulation was carried out using the TRACK code [?], in which the 25 kV  $^{129}\text{Xe}^{29+}$  beam particle distribution in 4-D phase space at the ion source exit (presented in Ref. [?]) was imported as the initial condition.

First, simulation was performed with solenoid strengths corresponding to specifications in the initial design by Trace-3D. Figure 3 shows the beam envelope from the ion source exit to FC2, with the fields of SN1, SN2, and SN3 being 2455 Gs, 3000 Gs, and 3000 Gs, respectively. It reveals an asymmetrical beam, differing from the Trace-3D simulation (Fig. 2). Figure 4(a) shows the beam emittance evolution along the line in both horizontal and vertical directions, demonstrating obvious emittance blowup at FC2 with serious distortion in phase space, as shown in Fig. 4(b). Since space charge effect is not taken into account in this simulation by assuming zero beam current, the projection emittance growth is mainly due to transverse coupling of the beam, plus slight effects of aberrations in the magnets. This means that in the existing operation scheme of the SECRAL associated line, the coupling of the beam from the ion source is intensified by the solenoid lenses, thereby increasing the horizontal and vertical projection emittances.

As mentioned previously, to achieve minimum projection transverse emittance, the transverse coupling of the ion beam should be dissociated. It was described in Ref. [?] that when the solenoid lens SN1 is loaded with -180 A (corresponding field strength of -2455 Gs; the negative value means the beam transmits opposite to the solenoid lens axial field direction in the beam pipe), the ion beam (25 kV  $^{209}\text{Xe}^{29+}$ ) reaches a decoupled condition. However, the solenoid lenses SN2 and SN3 also cause transverse phase space coupling because the ion beam remains asymmetric even though SN1 has disentangled the initial coupling from the ion source. Since SN2 and SN3 have identical configurations, if these two lenses are loaded with the same current values but opposite polarities, their combined transfer matrix will be:

$$R = R_{sol+} * R_{sol-} = \begin{pmatrix} \# & \# & 0 & 0 \\ \# & \# & 0 & 0 \\ 0 & 0 & \# & \# \\ 0 & 0 & \# & \# \end{pmatrix}$$

which will not give rise to transverse correlation.

shows simulated horizontal and vertical projection emittances and their products at different field strengths of SN1, SN2, and SN3. It can be seen that when the SN1, SN2, and SN3 fields are -2455 Gs, 3500 Gs, and -3500 Gs or -2455 Gs, -3500 Gs, and 3500 Gs, respectively, the projection transverse emittance is minimized, representing the optimal beam condition. Figures 5 and 6 show the simulated beam envelope, projection transverse emittance evolution, and phase space distributions under this condition. The transverse emittances in the horizontal (X) and vertical (Y) directions in Fig. 6(b) differ markedly from each other, with much smaller distribution areas and far less serious phase space distortions than those in Fig. 4(b).

#### IV. Experimental Results

The above simulations provided a new operation scheme for the SECRAAL associated line to improve beam quality: first, adjust the solenoid lens SN1 to disentangle the coupling from the ECR ion source and provide required focusing; second, configure solenoids SN2 and SN3 with different field directions but similar focusing strengths. The vertical line is responsible for matching the beam to the SFC. This scheme was tested in recent accelerator operation for an 18.9 kV  $^{86}\text{Kr}^{17+}$  beam provided by SECRAAL. The  $^{86}\text{Kr}^{17+}$  beam currents measured at FC1, FC2, FC3, and FC4 (before injection, as shown in Fig. 1) and at the extraction exit of SFC were 88  $\mu\text{A}$ , 81  $\mu\text{A}$ , 73  $\mu\text{A}$ , 66  $\mu\text{A}$ , and 5.9  $\mu\text{A}$ , respectively. Therefore, the transmission efficiency of the injector line to SFC can be estimated at 75%, compared to 51% in previous operations, while the overall efficiency of SFC in this operation is 6.7%, which is almost doubled.

#### V. Particle Beam Decorrelation for High-Intensity Ion Beams

As mentioned previously, the primary role of SN1 is to provide pre-focusing and size control of the beam entering the analyzing magnet, which is especially critical for high-intensity ion beams where space charge effects become the main cause of beam divergence. Previous studies [?] indicated that increasing the initial focusing strength is beneficial for reducing beam emittance growth by avoiding large-radius aberrations in the analyzing magnet [?]. As an example, Figure 7 shows a series of measured emittances under different solenoid currents after the analyzing magnet BM1 (at the EMD position) for a 110  $\mu\text{A}$   $^{40}\text{Ar}^{9+}$  beam with a total drain current of 1.7  $\text{mA}$  under 23.6 kV extraction voltage.

A simulation was performed for the 25 kV  $^{209}\text{Xe}^{29+}$  beam, taking space charge effects into account. The projection emittances in both horizontal and vertical directions and their product under different solenoid field strengths are illustrated in Fig. 8. The trend of change in projection emittance agrees well with experimental observations. The minimum projection emittance occurs when the solenoid field is largest (-4098 Gs). However, this is not the condition for particle beam decorrelation (the corresponding field strength for decorrelation is -2455 Gs as mentioned previously), and therefore the particle beam is not of optimal quality.

The challenge is how to simultaneously meet the beam focusing requirements from SN1 and disentangle the coupling for high-intensity ion beams. It is clear that a single solenoid lens cannot accomplish both tasks; at least one additional optical element capable of rotating the beam must be introduced. A skew magnetic quadrupole or a solenoid could serve as a candidate. As a proposal, Figure 9 illustrates a modified Q/A selection system in which another solenoid is employed just between the slits and the test chamber for coupling decorrelation compensation, where the desired ion species can be selected. Figure 10 shows the simulated beam projection emittance and their product as a function of the compensation solenoid field strength at an SN1 field magnitude of -4098 Gs. The figures demonstrate that with the help of this solenoid, the projection emittance is somewhat decreased and the product is minimized at a solenoid field of around 1900 Gs, under which condition the ion beam can be considered “decoupled.”

## VI. Conclusion

Beam simulations have been performed to investigate the injector line for the SFC based on recent research on the transverse coupling property of beams from ECR ion sources. It is predicted that one possible cause of low transmission efficiency is that beam coupling is intensified by the solenoid lenses in the SECRAL associated line, resulting in projection transverse emittance blowup. An improved operation scheme for the SECRAL associated line has been proposed: first adjust the solenoid lens SN1 to disentangle the coupling, then configure SN2 and SN3 with equal field strength magnitude but opposing polarities. An experiment using this scheme was carried out, which shows that the overall efficiency of SFC is almost doubled, and the injector line efficiency increased by approximately 24%. Finally, a modification proposal for the Q/A selector system of SECRAL is presented to address high-intensity ion beams, which has been verified through subsequent simulations and proven to be reasonable and feasible.

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