Beam Dynamics Studies of ECR Injections for the Coupled Cyclotron Facility at NSCL *

X. Wu1) D. Cole M. Doleans G. Machicoane F. Marti P. Miller J. Stetson
M. Steiner P. Zavodszky Q. Zhao

(National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824, USA)

Abstract The Coupled Cyclotron Facility (CCF) has been operating at the NSCL since 2001, providing up to 160MeV/u heavy ion beams for nuclear physics experiments. Recent steps, particularly the improvement of the ECR-to-K500 injection line, were taken to improve the CCF performance. For that purpose an off-line ECR source, ARTEMIS-B, was built and used to investigate the impact on beam brightness under various source operating conditions, different initial focusing systems and current analysis dipole. Beam dynamics simulations including space-charge and 3D electrostatic field effects were performed and beam diagnostics including emittance scanner were used, leading to a better understanding of the CCF beam injection process. New initial electrostatic focusing elements such as a large-bore quadrupole triplet and a quadrupole double-doublet with compensating octupole were tested, and a new beam tuning procedure was established to improve the beam brightness for the CCF. Following these efforts, a significant increase of primary beam power out of the CCF has been achieved.

Key words ECR injection, electrostatic quadrupole focusing, analysis dipole

1 Introduction

Primary beam power achieved from the CCF has steadily increased since its commissioning in 2001[1]. Recent R&D for CCF has been focused on the improvement of the beam injection efficiency into the K500 superconducting cyclotron in order to improve the overall CCF performance and reach reliably 1kW primary beam power for experiments. An off-line ion source, ARTEMIS-B, has been built and commissioned in 2005[2], and was used as an R&D test stand to increase beam intensity and brightness for the CCF. Recent R&D efforts include beam dynamics studies using both beam simulations and experimental beam tests in the optical system after the ECR ion sources. As shown in Fig. 1, the optical system after each ECR ion source of the CCF has two components, an initial focusing system to focus the multi-species ion beams after its extraction from the ECR, and a 90-degree analysis dipole magnet to select the beam

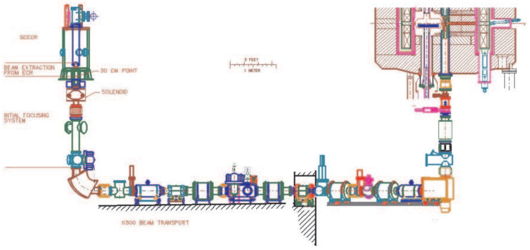

Fig. 1. Layout of the CCF injection beam line. The beam is extracted from the ECR ion source (top left) and injected into the K500 cyclotron (top right) via the injection beam line. Two ECR ion sources are used for CCF injection.

Received 20 April 2007
* Supported by National Science Foundation under grant PHY-0110253
1) E-mail: xwu@nscl.msu.edu

of interest. Results from the beam dynamics studies for those two components are presented, and the benefit to CCF operation is discussed in this paper. Details of the ARTEMIS-B experimental set-up and measurement results for the studies are given in[3].

2 Initial focusing system studies

In the CCF injection line, solenoids were initially used to focus the beams extracted from the two ECR production ion sources (ARTEMIS-A and SCECR) into the analysis dipole magnet below. Though good beam transmission (~80%) after the analysis dipole was achieved, the injection efficiency into the downstream K500 cyclotron was usually low[4].

Through beam dynamics simulations, non-linear effects from space charge forces[5, 6] were shown to be responsible for some beam brightness degradation when a magnetic solenoid element is used to focus the multi-species ion beams extracted from an ECR ion source. The non-linear forces are due to the shorter focal length for ion species with larger Q/A ratio than the beam of interest. To alleviate this problem, it was proposed to use an electrostatic quadrupole triplet in place of the solenoid between the ECR and the dipole magnet. When such an electrostatic focusing system is used, the beam envelopes for the different ion species are similar between the ECR and the analysis dipole magnet. Thus, the space charge forces remain more linear and their degrading effect on the beam brightness is minimized.

Nonetheless, compared to the solenoid, using electrostatic quadrupoles has its own limitations. Firstly, the two transverse planes are not focused simultaneously like in the solenoid focusing case. As a consequence, beam envelopes are larger and the beam transmission through the initial focusing system is usually reduced. Secondly, intrinsic non-linear focusing forces in the fringe field regions of the electrostatic quadrupoles[7] can significantly degrade the beam brightness. Design studies for electrostatic initial focusing system were performed to address these two issues. The first system was a commercially available Small Bore electrostatic Triplet (SBT) installed under the SCECR ion source of the CCF in September 2004 to test the potential benefit of the electrostatic focusing option. The injection efficiencies into the K500 cyclotron were satisfactory, showing improvement from solenoid, but overall transmission through the SBT was poor. To increase the beam transmission, a Large Bore electrostatic Triplet (LBT) was subsequently used. To reduce the effect of the non-linearities of the electrostatic quadrupoles on the beam brightness, a double electrostatic quadrupole doublet (DD) with a correcting electrostatic octupole was eventually designed and installed. The two later designs, LBT and DD, were thoroughly tested on ARTEMIS-B and the tuning procedure to achieve maximum beam brightness was established prior to their installation on the CCF injection beamline.

2.1 Small bore electrostatic quadrupole triplet

The inner and outer electrodes of the SBT have an aperture of 76.2mm and lengths of 100 and 50mm, respectively. In addition, a collimator with an aperture of 50mm was installed in front of the triplet to protect the first electrode from the beam. Significant beam losses on the entrance collimator and inner electrodes were observed experimentally and the transmission through the SBT and dipole magnet was estimated to be ~20%. In addition to the poor transmission, beam simulations performed using KOBRA3-INP code[8] for $^{40}Ar^{7+}$ beam also showed significant degradation of the beam emittances in both transverse planes due to the field aberrations in the SBT, leading to poor beam brightness. The beam transverse phase spaces after focusing through the SBT are shown in Fig. 2.

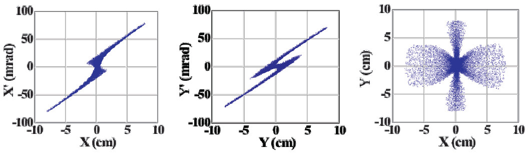

Fig. 2. Transverse phase spaces for $^{40}Ar^{7+}$ beam after SBT.

2.2 Large bore electrostatic quadrupole triplet

To improve beam transmission, a large bore electrostatic quadrupole triplet was designed. The inner and outer electrodes of the LBT have an aperture of 152.4mm, and lengths of 200 and 150mm, respectively. The entrance collimator aperture is also increased to 100mm. The electrodes were lengthened compared to the SBT to limit the required electrode voltages due to the increase of the aperture of LBT. Beam simulations were also performed for $^{40}\text{Ar}^{7+}$ beam, and the transverse phase spaces after the LBT are shown in Fig. 3. Due to the larger bore radius, the transmission through the LBT was improved. Also, the longer electrodes helped reduce the aberrations[7], leading to significantly reduced beam phase space distortions, especially in the horizontal plane. Overall, the LBT has significantly improved the beam brightness compared to the SBT.

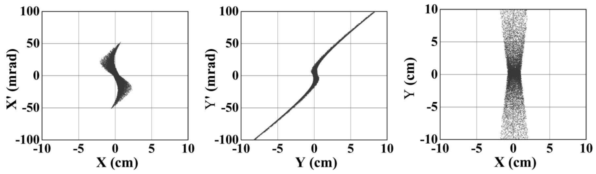

Fig. 3. Transverse phase spaces for $^{40}\text{Ar}^{7+}$ beam after LBT.

2.3 Electrostatic quadrupole double doublet with compensating octupole

To further reduce the aberrations, an Electrostatic Quadrupole Double Doublet (DD) with compensating octupole was designed. The DD has two outer quadrupoles with 120mm apertures and 100mm length and two inner quadrupoles with 160mm aperture and 200mm length. The compensating octupole has an aperture of 160mm and is located after the first doublet. Baartman's analysis[7] shows that the aberrations in electrostatic quadrupoles depend on the cube of the distance to the beam axis. Therefore, an active compensation for quadrupole aberrations can be obtained using octupoles. The largest beam size occurs in the second focusing quadrupole. Thus, an electrostatic octupole was added after the first doublet to compensate for the aberrations introduced by the second quadrupole. Beam simulations were performed for $^{40}\text{Ar}^{7+}$ beam and the transverse phase spaces after the DD with octupole compensation are shown in Fig. 4. Compared to previous electrostatic focusing systems, distortions in both horizontal and vertical phase spaces have been significantly reduced and the beam brightness increased.

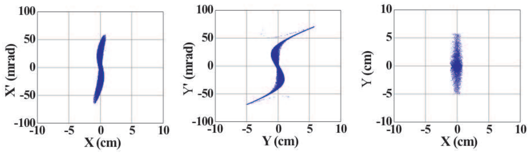

Fig. 4. Transverse phase spaces for $^{40}\text{Ar}^{7+}$ beam after DD.

Figure 5 shows the performance comparison for all electrostatic focusing elements from beam simulations. In good agreement with design considerations, the beam simulation results indicate that the DD is the best focusing system. For the ~100π mm·mrad transverse acceptance of the K500 cyclotron the beam brightness is ~30% better after the LBT, and ~55% better after the DD, than after the SBT, respectively.

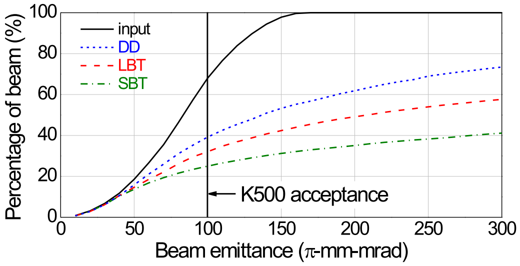

Fig. 5. Percentage of included $^{40}\text{Ar}^{7+}$ beam vs. emittance for different electrostatic focusing systems.

In addition to the better beam brightness, the DD also offers more flexibility than a triplet focusing system to control beam sizes and divergences for both transverse planes in the downstream analysis dipole magnet. This flexibility is beneficial because further beam dynamics study showed that the analysis dipole currently used could severely degrade the beam brightness if the beam size in the bending magnet is too large.

3 Analysis dipole studies

A beam-based experiment on ARTEMIS-B was performed to quantify the effect of the dipole magnet on the beam brightness[3]. The results indicated that the analysis dipole has a strong sextupole field component with an integrated field errors of ∼1% within 25mm of the aperture and ∼5% within 50mm. A numerical model for the analysis dipole was established based on the experimental results. In this model, thin sextupoles were added at both ends of an ideal dipole magnet to represent the field aberrations. The strength of the sextupoles was then adjusted until the experimental results were properly reproduced. Using the model, the effect on the beam brightness was investigated and it was concluded that limiting the beam size through the dipole under 25mm was critical to avoid severe degradation of the beam brightness, regardless what initial focusing element were used in the system.

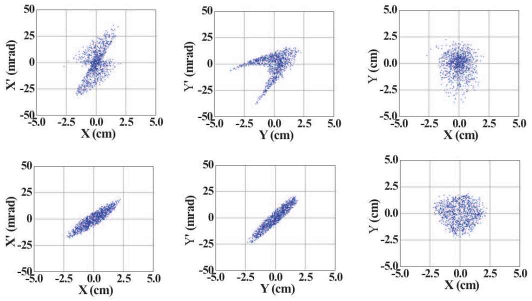

Fig. 6. Transverse phase spaces for $^{40}\mathrm{Ar}^{7+}$ beam after solenoid focusing and dipole magnet. The solenoid is tuned for an average beam size in the dipole of ∼50mm (top row) and ∼25mm (bottom row).

This requirement poses a strong constraint on the tuning of the initial focusing system above the analysis dipole. As an example, simulated phase spaces for a $^{40}\mathrm{Ar}^{7+}$ beam after the dipole magnet are shown in Fig. 6 in the case of a solenoid focusing for two different focusing situations into the analysis dipole. For clarity, no space charge effects were included in the simulations. The beam emittances are significantly more degraded in the first solenoid tune than in the second due to the larger beam size and the effect of the field aberrations in the analysis dipole in this case. Fig. 7 shows the beam size at the entrance of the analysis dipole and the resultant beam brightness for different focusing strengths of the solenoid. Variations of the beam brightness as a function of the beam size in the analysis dipole were also observed experimentally[3].

Results from Fig. 7 indicate that an optimal tune for the solenoid exists to mitigate the degradation of the beam brightness in the analysis dipole. This conclusion is valid for any focusing system used between the ECR ion source and the analysis dipole. To apply this optimal tuning procedure and limit beam brightness degradation, a 25mm aperture was installed before and after the analysis dipole. For the three focusing systems tested on ARTEMIS-B (solenoid, LBT and DD), it was found that the optimum beam transmission did not coincide with optimum beam brightness due to the field aberrations in the analysis dipole.

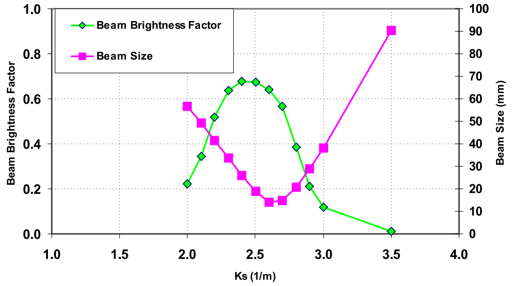

Fig. 7. Beam size entering the analysis dipole and resultant beam brightness with respect to the solenoid focusing strength.

4 Improvements of CCF beam injection

Results from beam simulations and experimental studies on ARTEMIS-B have been valuable to understand and optimize the beam brightness for various initial focusing systems and for the current analysis dipole magnet. The tuning procedures devised on ARTEMIS-B for the LBT and DD were found to be beneficial once these systems were installed in the CCF injection beamline. Electrostatic devices as initial focusing systems have proven successful in CCF operation.

Table 1 summarizes the highest beam intensities accelerated in the K500 cyclotron during CCF operation for various initial focusing systems and various ion beams. Comparison between different initial focusing systems must take into account additional factors such as the performance of the ECR ion sources used and K500 cyclotron operating conditions. For example the SBT is installed under the SCECR whereas the LBT and DD were installed under ARTEMIS-A. Nonetheless, recent efforts to improve the beam injection line performance have been very successful as shown in Table 1. Using the DD installed in July 2006 under ARTEMIS-A, ∼1kW of beam power on production target for a 140MeV/u ^{48}Ca^{20+} was achieved for the first time at the CCF.

Table 1. Maximum beam intensities (eμA) accelerated in the K500 cyclotron during CCF operation for different initial focusing systems and different beams.

	^{40}Ar^{7+}	^{48}Ca^{8+}	^{78}Kr^{14+}	^{136}Xe^{20+}
Solenoid	3.1	2.0	5.0	1.5
SBT	5.3	2.6	5.5	2.3
LBT	9.5	3.3	8.2	2.6
DD	20.0*	5.1	–	–

*Beam measured inside K500 cyclotron, not extracted from K500 at full beam intensity yet.

5 Conclusion

Beam dynamics studies for CCF injection using beam simulations and beam experiments with off-line ARTEMIS-B test stand have lead to significant increase of the beam power in the CCF. Further beam dynamics studies will include the continuing beam tests of DD in CCF injection line and possibly designing a new analysis dipole in 2007 in order to reduce field aberrations and expand the beam tuning ability. Adding an einzel lens in front of the LBT to further improve its performance is also being explored.

References

1 Závodszky P A et al. HEP & NP, 2007, **31**(Suppl. I): 18 (in Chinese)
(Závodszky P A 等. 高能物理与核物理, 2007, **31**(增刊 I): 18)

2 Machicoane G, Cole D, Ottarson J et al. Rev. Sci. Instr., 2006, **77**: 03A322

3 Machicoane G et al. HEP & NP, 2007, **31**(Suppl. I): 187 (in Chinese)
(Machicoane G 等. 高能物理与核物理, 2007, **31**(增刊 I): 187)

4 Stetson J W, Machicoane G, Miller P et al. Experimental Studies of Electrostatic and Solenoidal Focusing of Low Energy Heavy Ion ECRIS beams at NSCL/MSU, proceedings of the XXIII Linac Conference, Knoxville, Tennessee, August 2006

5 Kazarinov N Yu. Rev. Sci. Instr., 2004, **75**: 1665

6 ZHAO Q, Balabin A, Marti F et al. Simulations of Solenoid and Electrostatic Quadrupole Focusing of High Intensity Beams from ECR Ion Source, proceedings of PAC 2005, Knoxville, Tennessee, May 2005

7 Baartman R. Aberrations in Electrostatic Quadrupoles, TRI-DN-95-21, TRIUMF, June 1999

8 Spaedtke P. KOBRA3-INP, 2005