A COMPARISON OF ELECTROSTATIC AND MAGNETIC FOCUSSING OF MIXED SPECIES HEAVY ION BEAMS AT NSCL/MSU

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Abstract

Beams extracted from ECR ion sources are a mixture of several ions and many charge states. Solenoid focusing of such beams can maintain cylindrical symmetry and allow longitudinal motion of secondary electrons for full space charge compensation. Electrostatic focusing does not create multiple intermediate focii of ions with differing charge-to-mass ratios, yet locally destroys space charge compensation. To explore these issues, an electrostatic triplet was installed in place of the present solenoid lens as the first focusing element of the "Artemis" ECR ion source (RT-ECR) beam line. It was then removed and re-installed under the superconducting ECR ion source (SC-ECR) for more extensive testing. This test installation was successful with significant beam intensity gains achieved over the solenoid configuration. Motivations for and results of these tests are discussed.

INTRODUCTION

The National Superconducting Cyclotron Laboratory at Michigan State University has been running with two cyclotrons coupled together since October 2000 [1]. One of two ECR sources is used to produce beam for injection into the K500 cyclotron, which is then injected into the K1200 cyclotron, sent through a thin stripper foil (Q_2/ Q_1 ≈ 2.6) and accelerated to full energy. A layout drawing of the first part of the beam line under the SC-ECR is given in Figure 1. The extraction potential ranges from about 22 to 26 kV depending on the centering requirements of the K500.

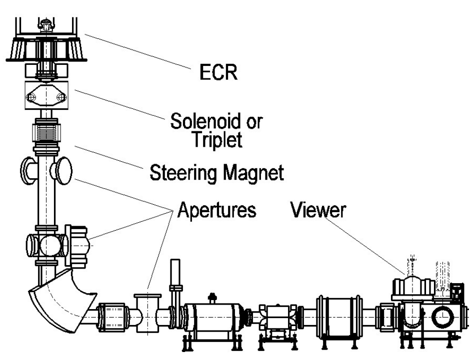

FIGURE 1. Injection beam line layout. The distance from ECR to analysis magnet ≈ 2.2 m.

During the transition from initial commissioning to routine operations, it was clear that both ECR's produced a lot of beam that could not be transmitted through the K500. A first step to control this mismatch and protect K500 components was to install three sets of circular collimators (Figure 1), thereby restricting the 150 mm beam line bore to 25, 17, 12.5 or 7.5 mm as desired. Consequently, there was a huge drop of beam current in the injection line over the "open" state, but without a resultant drop in beam from the K500 (Table 1).

TABLE 1. Using injection line apertures reduces beam intensity going into the K500 without affecting output.

Apertures [mm]	Beam	Analyzed Beam [eμA]	K500 Inflector [eμA]	K500 Extracted [eμA]
none	$^{16}O^{+3}$	400	159	1.1
7, 12, 25	$^{16}O^{+3}$	36	5	1.1

Such results point to a matching problem between the ECR output beam and the acceptance window of about 75π*mm*mr presented by the K500. However using beam collimated by these aperatures, transmission from the K500 inflector to K1200 extraction is quite good, often 8 - 10%, easily within a factor of 2 of what is reasonably achievable. Therefore any large increases of beam intensity from the K1200 must come from an increase in *useable* beam injected into the K500.

RINGS

In tuning of the injection lines in their original ECR-Solenoid configuration, it was repeatedly noted that the analyzed beam had a pronounced tendency to be hollow. An example is shown in Figure 2. (Viewer plates for imaging the analyzed beam have proven invaluable in understanding overall beam behavior that would not be so easily noted using wire scanners or their equivalent).

FIGURE 2. Images of $^{40}Ar^{+7}$ beam with solenoid focusing. On the left, helium used as a support gas in the source. Shutting off the helium gas supply results in the image on the right. Peak of charge distribution is $^{40}Ar^{+9}$.

One explanation of this ring formation is "short focusing" by the magnetic solenoid of beam components with charge/mass ratios higher than the desired beam [2]. Higher Q/A beam components are brought to sharp focii before reaching the analysis magnet. These focii inside the column of desired beam lead to a high space-charge condition driving the lower Q/A beam radially outwards. Further experiments, such as the one shown in Figure 3, support this hypothesis. One solution as suggested by R. Baartman is to replace magnetic by electrostatic focusing so that all ion species are focused identically until bent by the magnetic 90 degree analysis magnet, as is done at TRIUMF.

FIGURE 3. ECR is tuned to produce ^{48}Ca of about 100 eμA summed over all charge states. The support gas is helium of about 1200 eμA. Here, the solenoid and analyzing magnet are set first to select $^{48}Ca^{+8}$, then $^{4}He^{+1}$ and finally $^{4}He^{+2}$. Since the intensity of ^{48}Ca in charge states higher than 8+ is low, the ring in the first picture is produced by short focusing of both helium charge states. The ring for the $^{4}He^{+1}$ case is smaller because only the 2+ helium is short focused. In the third case, the $^{4}He^{+2}$ beam is itself the highest Q/A beam component, so there is no overfocusing, hence no ring.

TRIANGLES

In order to expeditiously test the ring formation hypothesis and make a first attempt to eliminate it, an electrostatic quadrupole triplet was purchased (National Electrostatics Corp. Model EQTS76-15). The nominal aperture is 76 mm, but a water cooled collimator of 50 mm aperture was installed on the upstream side of the triplet to protect the focusing elements from direct beam. The solenoid underneath the RT-ECR was removed and the triplet was installed in late June 2004.

With the triplet in place, it was immediately noted that the fundamental character of the beam images was radically altered and rings were no longer evident. Beams tested initially were 140 MeV/u ^{40}Ar, ^{58}Ni at 140 and 160 MeV/u and 140 MeV/u ^{48}Ca. With the 58Ni beam, K1200 extracted beam intensity was up a modest 10% over the previous best run value, but a dramatic increase to record high transmission efficiencies was observed (Table 2).

TABLE 2. "Solenoid vs. Triplet" results for 58Ni at 140 Mev/u with the RT-ECR. The efficiency figures factor out unavoidable stripping loss at K1200 injection.

Analyzed Beam [eμA]	K500 Inflect [eμA]	K500 out [eμA]	K1200 out [enA]	trans-mission %
40	11	1.9	270	0.8
2	2	0.6	270	16

However during the course of these tests, a problem with the RT-ECR occurred whereby the field of one of the permanent magnets of the sextupole was weakened relative to the others, compromising source performance. Because the 50 mm aperture on the triplet was small compared to that of the 150 mm opening thru the solenoid, the solenoid was reinstalled to better accommodate unusual beam asymmetries until a matched set of permanent magnet pole pieces can be fabricated.

Mid-September 2004, the triplet was installed in place of the focusing solenoid under the SC-ECR and a series of test beams were run. Within a short time very interesting beam images were obtained. An example is shown in Figure 4.

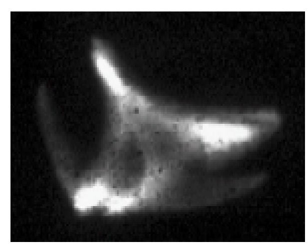

FIGURE 4. Image of $^{16}O^{+3}$ beam with electrostatic quadrupole triplet focusing under the SC-ECR. The distance between bright spots is 3 cm.

Each lobe of this triangle is about the same intensity. Any one lobe can be individually steered to be on axis and accelerated in the K500 but no two lobes can be accelerated simultaneously (Table 3). There is very little beam in the center.

TABLE 3. Using steering through the apertures to produce analyzed $^{16}O^{+3}$ beams in quanta of 1/3 the total analyzed beam.

Apertures [mm]	Analyzed Beam [eμA]	K500 Inflector [eμA]	K500 out [eμA]
25 25 25	72	34	5.6
25 17 17	51	30	4.9
25 12 12	23	20	4.5

The appearance of what is essentially 3 beams where one is expected has a possible explanation revealed by recent x-ray images of the ECR source plasma [3] as shown in Figure 5.

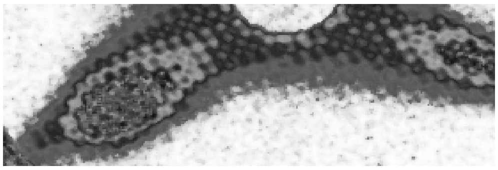

FIGURE 5. X-Ray image from the injection side of an ECR source plasma showing about half of the plasma region. The extraction aperture is top center. Ionization is occurring in 3 distinct, off-axis, regions [3].

INITIAL RESULTS

To date, the SC-ECR combination has been run for three weeks. Beams of ^{16}O at 150 Mev/u and ^{40}Ar, ^{78}Kr, and ^{124}Xe at 140 MeV/u have been tested. Calculations with KOBRA3d show that the beam size as it enters the triplet is 80 mm, larger than the 50 mm diameter collimator. Comparison of the total beam output from the ECR, estimated from the drain current on the high voltage platform vs. the sum of all beam currents measured after the analysis magnet, give transmission values of between 22 and 26% for the beams tested. This compares to 60-80% with the 150 mm bore solenoid. In spite of this restriction, the analyzed beam available with the triplet was comparable to that with the solenoid except in the case of ^{124}Xe, which was down considerably, possibly because of a lack of conditioning time between beam changes.

The ^{16}O, ^{40}Ar, and ^{78}Kr beams were tuned through the K1200. Final beam output was up by as much as 30% for the oxygen and 40% for argon. More importantly, the krypton beam intensity is up 70% over previous best results, reaching 46 particle nanoamps. This is the first beam to exceed the design goals given for the coupled cyclotron upgrade. As much as 1000 hours over the next year is expected to be run with ^{78}Kr, so such an increase is of considerable significance.

MODELS AND DIRECTION

It seems clear that accurate modeling of injection line behavior cannot be seperated from details of beam production in ECR sources. It seems equally clear that significant increases in useable beam current may be achieved with knowledge gained from more physically accurate models. For example, a particle-in-cell model of the NSCL layout with ion beam mixtures in the proportions and currents measured from our sources, shows the formation and disappearance of the beam rings (Figure 6). However in this model, the observed 3-fold symmetries observed in the real beam line do not appear because the starting beam shape is taken by the simulation as symmetrical at ECR extraction.

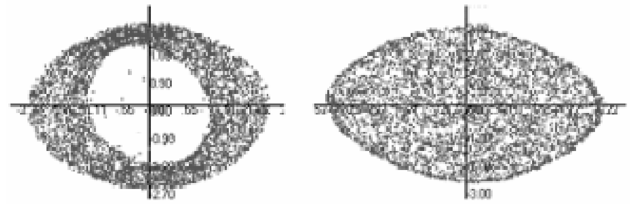

FIGURE 6. Calculated shapes of ^{40}Ar beam analyzed to 7+. With the solenoid, effects of 8+ 9+ and 10+ form a ring in x-y space (left). With the triplet, but with otherwise identical starting conditions, the beam ring does not form (right).

Inclusion of the details of ion production in the plasma chamber into beam simulations is difficult, but progress is being made and will be reported in detail at a later date (Figure 7).

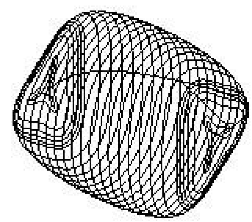

FIGURE 7. This figure shows a 3D representation of the calculated electron resonance surface inside the plasma chamber of the RT-ECR. Cross-sections taken near the center are nearly circular. Toward the ends, they become first triangular, then 3-lobed.

The solenoid confinement and sextupole fields inherent in ECR sources create x-y coupling and higher order terms that have been generally ignored in the past. A sextupole installed after the ECR may help bring the 3 pieces of beam back together in a useable form. A solenoid doublet may be able to minimize effective emittance growth due to cross coupling. Both options will be further explored at the NSCL.

ACKNOWLEDGEMENTS

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