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

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*Abstract*

Experience at the National Superconducting Cyclotron Laboratory has shown the first focusing element after the electron cyclotron resonance ion source (ECRIS), before the beam is analyzed by a magnetic dipole, to be critical to subsequent beam transport and matching. Until 2004, both ion sources at the NSCL used a solenoid as this first focusing element. Observation of hollow beam formation led to further analysis and the decision to replace the solenoid with an electrostatic quadrupole triplet on a test basis [1]. Substantial increases in net cyclotron output were achieved, leading us to adopt electrostatic quadrupole focusing as the permanent configuration. In addition, a sextupole magnet was installed in this beam line. Motivations for these changes and results of operating experience are discussed.

## INTRODUCTION

The National Superconducting Cyclotron Laboratory at Michigan State University consist of two cyclotrons coupled [2]. One of two ECR sources produces heavy ion beam for injection into the K500 cyclotron for acceleration. Extracted ions of about 12 MeV/u are transported into the K1200 cyclotron, sent through a thin stripper foil ($Q_2/ Q_1 \geq 2.4$) and accelerated to full energy. A layout drawing of the first part of the beam line under the Superconducting Ion Source (SCECRIS) is given in Figure 1. The layout for the Room Temperature Ion Source (RTECRIS) is similar. ECRIS extraction potentials range from 18 to 26 kV.

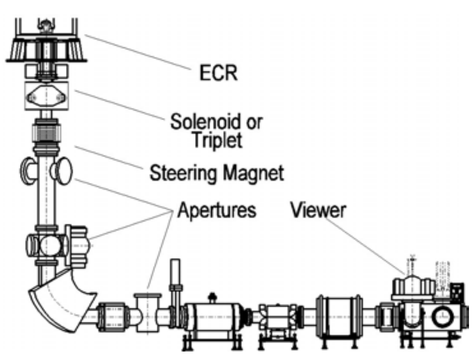


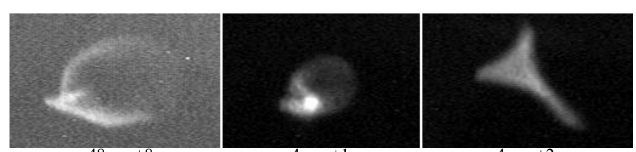

Figure 1: Injection beam line layout. The distance from ECR to analysis magnet is about 2.2 m.

During the transition from initial commissioning to routine operations, it was clear that both ECRIS's produced a lot of beam that could not be transmitted through the K500. Addition of apertures reduced significantly beam intensities transmitted to the K500, but allowed more beam to be usefully accelerated and extracted. Repeatedly during operation it was noted that opening the apertures resulted in a net loss of extracted beam from the K500.

Such results indicated 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 apertures, transmission from the K500 inflector to K1200 extraction was often quite good, 8 - 10%, within a factor of 2 or so of what is reasonably achievable. Therefore it became clear that any large increases of beam intensity from the K1200 must come from increases in useable beam injected into the K500 and investigations were undertaken to that end.

## RINGS

In the ECRIS-solenoid configuration, the analyzed beam has a notable tendency to be hollow. Examples and a small experiment are shown in Figure 2.



$^{48}Ca^{+8}$ $^{4}He^{+1}$ $^{4}He^{+2}$

Figure 2: Here, the ECRIS is tuned to produce $^{48}Ca$ of about 100 eμA summed over all charge states. The support gas is helium of about 1200 eμA. 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 and the source is properly imaged.



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The origin of these rings was shown in a paper by N.Yu. Kazarinov [3] and is due to the components of unanalyzed beam of charge to mass ratios higher than the beam desired after analysis. With magnetic focusing, the higher Q/A particles are brought to a sharp early focus before reaching the analysis magnet. Since the undesired components can be quite intense (> 1mA) this leads to high space-charge forces within the desired beam column which drive this beam radially outwards. One way to eliminate this problem is to use electrostatic focusing as with the TRIUMF injection line, where all accelerated beam components are focused equally until reaching the analysis dipole magnet [4]. A calculated comparison of the two focusing techniques is shown in figure 3.

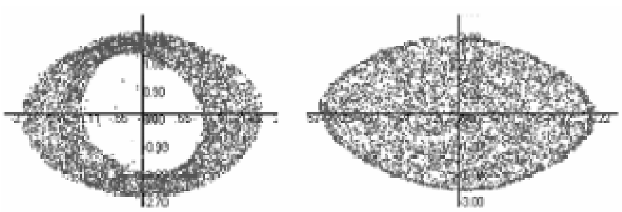

Figure 3: Shapes of $^{40}$Ar beam analyzed to 7+ as calculated with a particle-in-cell model [3]. In the solenoid case (left) effects of 8+ 9+ and 10+ form a ring in x-y space In the triplet case, but with otherwise identical starting conditions, the beam ring does not form (right).

## TRIANGLES

The magnetic solenoid under the SCECRIS was replaced with a 76 mm aperture electrostatic quadrupole triplet (National Electrostatics Corp. Model EQTS76-15). 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. With electrostatic focusing, it was immediately noted that the fundamental character of the beam images was radically altered and rings were no longer evident in beam images. An example is shown in Figure 4.

Figure 4: Image of an analyzed $^{40}$Ar$^{+7}$ beam using electrostatic quadrupole focusing under the SCECR.

The beam intensity within the triangle is very non-uniform, often so much so that only about 1/3 of the beam can be accelerated. In many cases, each "point" of the triangle can be accelerated equally well, but no two tips can be accelerated at the same time. The appearance of what is essentially 3 beams where one is expected is partly explained by x-ray images of an ECR source plasma [5] as shown in Figure 5.

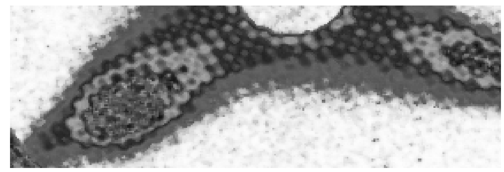

Figure 5: X-Ray CCD image from the injection side of an ECR source plasma showing about half of the plasma region. The extraction aperture is top center. Ionization is occurring in 3 distinct, off-axis, regions [5].

Additionally, particle tracking using KOBRA3d show that even using uniform initial beam distributions within the ECRIS plasma chamber, the sextupole radial confinement field results in a 3-lobe output beam [5].

## RESULTS

The SCECR-triplet combination has been in place since September 2004. Initial tests showed transmission efficiencies from the SCECRIS to after the analysis magnet of 20-30% rather than the 60 - 80% achieved with the 150 mm bore focusing solenoid. Even so, overall beam output from the cyclotrons was higher than in the solenoid case. Calculation with KOBRA3d showed a beam size as it enters the triplet of 80 mm, larger than the 50 mm diameter collimator. In January 2005, hardware was altered so the triplet could be remounted closer to the extraction electrode, and the first pair of apertures were removed, resulting in transmissions again up to 60%.

Beams of $^{16}$O and $^{36}$Ar at 150 MeV/u, and $^{40}$Ar, $^{40}$Ca, $^{78}$Kr, and $^{124}$Xe at 140 MeV/u were tuned through the K1200. Results are summarized in Table 1.

Table 1: Intensity Gains of Electrostatic focusing over Magnetic for Tested Beams Extracted from K1200. Beam output is essentially doubled. The $^{78}$Kr of 46 pnA is the first beam to reach the coupled cyclotron project design goals. The $^{16}$O beam at 425 pnA and $^{40}$Ar beam at 180 pnA are the first at NSCL to exceed 1 kW beam power.

| $^{16}$O | $^{36}$Ar | $^{40}$Ar | $^{40}$Ca | $^{78}$Kr | $^{124}$Xe |
|---|---|---|---|---|---|
| **1.78** | **1.86** | **1.91** | **1.45** | **1.78** | **2.80** |

The rapid increase in beam intensity over the last few months led to the decision to install an electrostatic triplet (with larger bore) under the RTECRIS. This triplet has been ordered from NEC for delivery in September 2005.

## SEXTUPOLE

The observed triangular beam shapes are far from ideal. In designing optical systems one traditionally starts with an object consisting of a uniform disk of particles, round in x-y space, with angles and position independent of one another, i.e., uncorrelated. For the case of transport from an ion source, an additional assumption is often made in placing this disk at the zero potential surface near the source extraction aperture. However, the X-ray images show that the production of ions in an ECRIS is highly non-uniform and our viewer plate images confirm this non-uniformity continues after extraction from the source. (The analysis magnet does have aberrations that are not fully corrected. However, beam collimated in such a way as to be very small in this dipole still shows a 3-lobe shape that cannot be explained by these aberrations.)

If the effective object of the beam line is a group of particles in a tri-lobe shape without spatial correlations, then any attempt to bring the three tips together in space with quadrupoles or solenoids will only increase beam divergence at that point. However, it was also noted that varying quadrupole elements after the analysis magnet resulted in surprisingly complicated "3-dimensional" behavior consistent with a highly correlated beam. It was supposed that if this correlation was largely the result of the sextupole confinement field of the ECRIS, then a sextupole external to the source could potentially use this correlation to benefit, making the beam "round", not only at a point, but along the rest of the transport line.

To explore this possibility further, in November 2004 an air-cooled sextupole (originally built for the S800 spectrometer beam line) was remounted and installed 0.5 m upstream of the analysis magnet for the SCECR. This sextupole has a 18 cm bore, 20 cm pole tip length and a maximum pole tip field of 1.9 kG at 13 amperes. It can be rotated by hand around the beamline axis through an angle of 120 degrees. Some first results are shown in Figure 6 below.

Figure 6: Images of $^{78}Kr^{14+}$ beam, first with the sextupole off, next with sextupole on (1.6 kG) but with an incorrect orientation, and last on with the orientation correct. $V_{ecr}$ = 23.82 kV.

Experimental observation (later confirmed by modeling), indicates that the field strength available in this sextupole is too low to fully correct the initial beam correlations induced by the ECRIS sextupole. However, by using beams of a higher Q/A than what is normally run allows this field strength to be effectively higher and for the image to be corrected at a point. A further drift from this point results again in a triangular beam shape (Fig. 7).

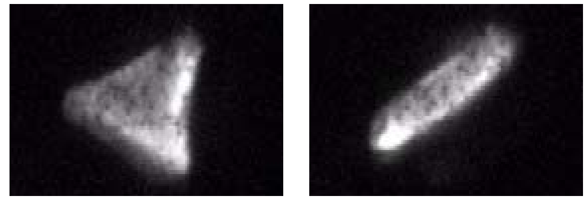

Figure 7: Images of $^{1}H^{1+}$ beam, first with the sextupole off and on (0.4 kG) with $V_{ecr}$ = 23.82 kV. The dispersion plane is rotated left by 45 degrees, so additional quadrupole focusing results in a round image.

## MODELS AND FUTURE DIRECTION

These experiences show that modeling of injection line behavior must take into account of the full range of ions and charges extracted and be intimately tied to the details of beam production in the real source confinement fields. Assumptions of a single ion species with initial beam uniformity and cylindrical symmetry are inadequate. With this in mind, recent calculations using an assortment of modeling codes indicate a scheme where the initial sextupole correlations from the source can be corrected with an external sextupole not only at one point, but permanently. With an additional correction for the axis rotation caused by solenoid fields, one essentially images an object that in reality never existed: an uncorrelated, "round" beam. This proposed scheme consists of replacing the triplet with an electrostatic doublet-octupole-doublet device followed by a stronger magnetic sextupole just above the analysis magnet [6]. (An electrostatic sextupole was considered but the voltages required would be uncomfortably high.) This device is being designed with installation for testing anticipated in late 2005.

## ACKNOWLEDGEMENTS

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