EXPERIMENTAL STUDIES OF ELECTROSTATIC AND SOLENOIDAL FOCUSING OF LOW-ENERGY, HEAVY-ION ECRIS BEAMS AT THE NSCL/MSU*

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Abstract

Replacement of the focusing solenoids between both production ECR Ion Sources and the beam analysis dipoles with electrostatic quadrupoles has resulted in a large increase in beam intensity available for nuclear physics experiments. 2D emittance scans have been employed in order to better characterize and improve injection line beams for various hardware configurations. Motivations and results of some of these measurements and operating experience are discussed.

INTRODUCTION

The National Superconducting Cyclotron Laboratory at Michigan State University consists of two cyclotrons coupled together [1]. Two ECR ion sources with extraction potentials of 18 to 26 kV are available for producing heavy ion beams for injection into the K500 cyclotron. From the K500, ions of about 12 MeV/u are transported into the K1200 cyclotron, sent through a thin stripper foil ($Q_2/ Q_1 \geq 2.43$) and accelerated to full energy, typically 90 – 160 MeV/u. A layout drawing of the initial part of the injection beam line under the 6.4 GHz Superconducting Ion Source (SCECRIS) is given in Figure 1. The layouts for the Advanced Room Temperature Ion Source (ARTEMIS) lines are similar.

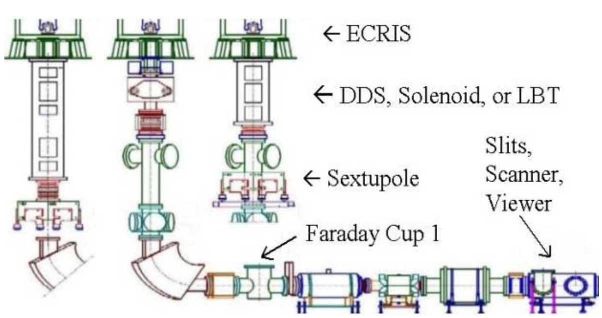

Figure 1: Injection beam line layout showing some element arrangements tested. The distance from ECR to analysis magnet is about 2.2 m.

In order to further ion source studies, a copy of this source (ARTEMIS-B) has been constructed with a diagnostic beam line as an independent test stand and was commissioned in late 2005 [2]. Both ARTEMIS-A and ARTEMIS-B are modified versions of the Berkeley AECR source (14 GHz, with permanent sextupole magnets, radial ports, and room temperature solenoids).

The need of the nuclear physics program to produce ever more exotic nuclei provides a strong motivation to increase available primary beam intensities. However, it was noted that increases of beam currents from the sources did not directly translate into increased accelerator output, especially when approaching loss limits of the deflectors. In many cases an increase of such current resulted in a net decrease of accelerator output and disproportionately higher losses. As a consequence, considerable effort has been made to improve matching the ECRIS output beam into the K500 acceptance of about 75π*mm*mrad.

HARDWARE ALTERATIONS

In September 2004, the focusing solenoid under the SCECRIS was replaced with an electrostatic triplet (National Electrostatics Corp. Model EQTS76-15). The bore diameter is 76 mm, but to protect the internal elements from direct beam, a 50 mm diameter water-cooled aperture was placed at the triplet entrance. This triplet provided significant increases in useable beam to the K500 compared to the previous arrangement, which motivated further development [3,4].

Significant recent hardware changes include:

1) A large bore electrostatic triplet (LBT) was delivered for the ARTEMIS lines with a 152 mm nominal bore diameter (EQTS152-10). The entrance collimator was also scaled proportionately from 50 to 100 mm diameter. The LBT was installed on the ARTEMIS-B test stand in December 2005, commissioned, removed and mounted on ARTEMIS-A in January 2006.

2) An electrostatic focusing system consisting of a quadrupole doublet, octupole, and a quadrupole doublet (DDS) was specified by NSCL and fabricated by NEC. (An octupole element was included to correct high order effects caused by the short electrode lengths and wide bores of the quadrupole elements). The DDS was installed on ARTEMIS-B in March 2006, tested and re-mounted on ARTEMIS-A in June 2006.

3) A water-cooled sextupole was modified for higher field strength and was installed under ARTEMIS-B in March 2006. (With the DDS giving a pi phase advance between the radial confinement sextupole of ECRIS and an external sextupole, simulations suggested a full correction of the beam correlations possibly induced by the source sextupole could be fully corrected hence reducing beam emittance [5]). (Some evidence of this

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effect has been measured using the air-cooled solenoid presently mounted under the SCECRIS.)

4) Emittance scanners of the Allison type were installed on both the production beam line and at the ARTEMIS-B test stand and fully commissioned by Fall 2005.

SOME RESULTS

Emittance scans on both the production and test beam lines quickly showed that traversing the analysis dipole can have a huge effect on beam emittance. No field map is available, so a series of beam measurements were performed and subsequently modeled showing that the dipoles have a transverse field variation of about 4%. Also, this dipole gives different focusing strengths in the bending (y) and non-bending (x) planes, which further complicates tuning.

With the LBT on the test stand, considerable time was spent to develop settings for the triplet elements that give the best brightness within 75*pi*mm*mrad. Previous to these tests, the triplet elements were set symmetrically to approximately equal voltages, which they in principle should be. However, with the “symmetric” tune, measured x and y emittances were very different. By raising the strength of the first element and greatly lowering the third, the total transmission to FC1 was generally less than maximal, but the useable brightness increased and the variation between the two transverse planes was greatly reduced. This “asymmetric” triplet setting was subsequently employed on both the SCECR and ARTEMIS-A beam lines with resulting increases in K500 and K1200 beam output.

By keeping the beam small as it goes through the dipole and correcting to some extent the dipole’s differing vertical and horizontal focal lengths, the bad effects can be minimized, but it both forces the focusing to be set in a very specific way and adds a degree of uncertainty in how accurately the measurements reflect source conditions. At least part of the advantage of the triplet over the solenoid is the availability of more adjustment parameters for dealing with a poor quality analysis magnet.

Some anticipated advantages of electrostatic over magnetic focusing have been discussed previously [3,4]. A more recent indication was given by simulations of ARTEMIS beam output with KOBRA3D and beam transport to a location in before the dipole [6]. When space charge effects were included in a normal way, the low-emittance portion of the beam was degraded in the solenoid case relative to the LBT (Fig. 2).

Measured brightness from ARTEMIS-B (of necessity taken with beam after the dipole) for the solenoid, LBT and DDS cases are shown in Figure 3. The DDS shows a clear advantage. The LBT shows only a slight advantage over the solenoid and only at the smallest emittances.

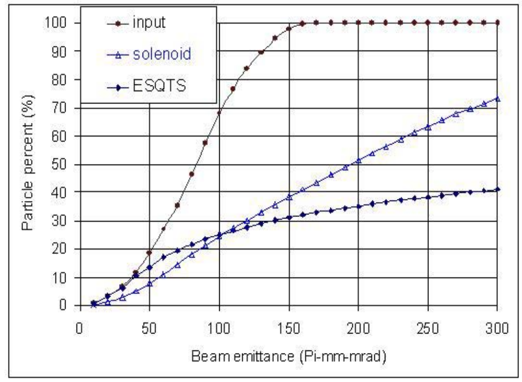

Figure 2: Percentage of total beam vs. beam emittance from a simulated output of ARTEMIS. The solenoid transmits more beam at higher emittance, but less at the low emittance required for K500 injection.

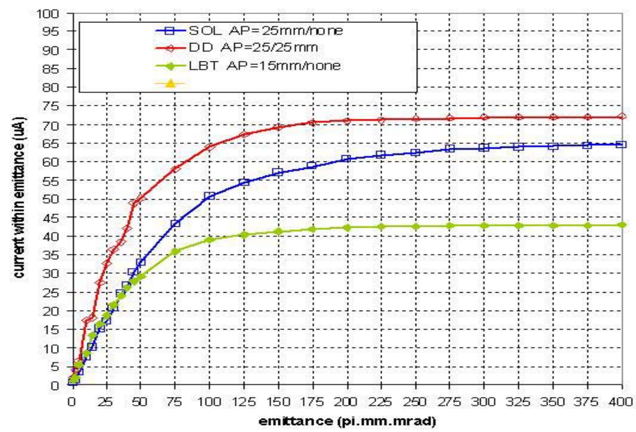

Figure 3: Measured $^{40}Ar^{7+}$ current contained within a defined emittance with the DDS (top line), solenoid (middle), and LBT (bottom). Switching the octupole element of the DDS on results in ~10% gain in beam current compared to off.

Table 1: Measured brightness of selected beams and resultant transmissions through the K500 cyclotron. The beams listed are $^{40}Ar^{+7}$ (48 µA), $^{40}Ar^{+7}$ (59 µA), and $^{36}Ar^{+7}$ (21 µA), respectively. Extracted beam energy is about 12.5 MeV/u

Beam inside 100 pi (x,y)	**Beam inside 50 pi (x,y)**	**K500: (extracted/ injected)**
55% , 39%	34%, 19%	11%
75% , 62%	51%, 36%	17%
100%, 99%	94%, 99%	35%

Emittance scans taken in the injection line during routine operation show a strong relationship between measured beam quality and accelerator performance (Table 1). A plot of the best case in Table 1 is shown in Figure 4.

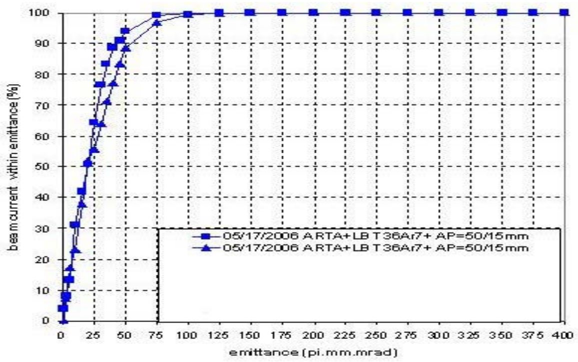

Figure 4: Percentage of total beam vs. emittance is plotted for $^{36}Ar^{+7}$ in the best case from Table 1.

Images of beams taken after the analysis magnet almost always show a complicated structure [3,4]. However, since injection line beam imaging at the NSCL has been done only after the analysis dipole and emittance measurements have demonstrated that aberrations in this device can greatly influence the beam, these images alone cannot directly prove that the beam coming from the ECRIS source itself has a complex structure. A recent cooperation between NSCL and GSI however removes much of that doubt [6]. Images taken at GSI in July 2006 show that a complicated beam structure exists without any intervening optical device (Figure 5).

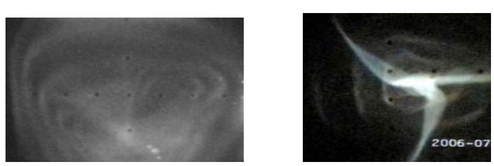

Figure 5: Images taken with BaF-coated view plates and CCD camera of ^{40}Ar beam in Darmstadt on the GSI test line. The left image is from a viewer 50 cm from the ECRIS plasma electrode with no intermediate focusing. The right image is taken about 2 m downstream with focusing by a solenoid. The “star” appears when a ring of a particular rigidity is focused more strongly.

The visually observed 3-fold symmetry suggests a 2nd order correlation but such correlations in general were not observed in 2-dimensional emittance scans when the beam was tuned with asymmetric triplet settings. Perhaps 4D measurements using a pepper pot or with an additional slit in front of the emittance scanners will clarify this further.

Initial experiments with the DDS and strong external sextupole failed to improve the measured beam quality. However, the calculated settings to achieve full correction of possible 2nd order components to the beam from ARTEMIS-B require the beam to be very large in the dipole and in that situation, aberrations caused by the present dipole completely dominate. Further experiments along these lines must wait until the dipole problem is corrected.

SUMMARY

The net output of the NSCL coupled cyclotrons has increased significantly each year since 2002 largely due improvements in the low-energy injection line (Figure 6). The DDS shows improvement over the LBT, but has not been fully developed as of this writing. Electrostatic quadrupoles presently show operational advantages over solenoidal focusing for reasons not yet fully clear. Replacement of the present analysis magnet dipoles, now planned for Summer 2007, is expected to further improve injected beam quality and net accelerator performance. The ability to test, debug, and optimize various ion source configurations off-line has proven a vital tool in improving accelerator performance.

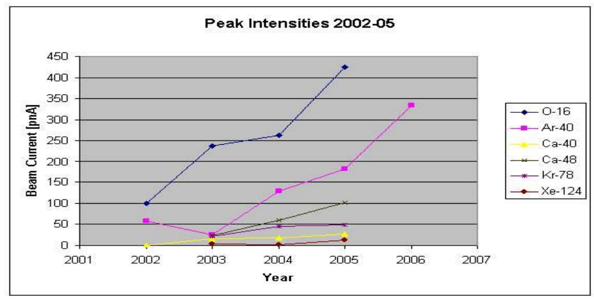

Figure 6: Peak current extracted (at ~140 MeV/u) by year from 2002 to mid-2006. Beams are O, Ar, Ca, Kr, and Xe. A peak beam power of 2 kW was achieved with ^{40}Ar in January 2006 with more sustained values of ~1.5 kW.

ACKNOWLEDGEMENTS

The authors wish to thank Marc Doleans, Xiaoyu Wu at the NSCL as well as Jan Mäder and Peter Spädtke at GSI for their contributions.

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