THE DESIGN OF THE ISOCHRONOUS AND ACHROMATIC CHARGE-STRIPPING SECTIONS FOR THE RARE ISOTOPE ACCELERATOR*

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Abstract

The proposed Rare Isotope Accelerator (RIA) will use a superconducting, cw linac to accelerate light and heavy ions to final energies of ≥ 400 MeV/u with a beam power of 100 to 400 kW. To meet the beam power requirements, simultaneous acceleration of several charge states is proposed for the heavier ions. For example, for U^{238}, two charge states (28+, 29+) would be accelerated to an energy of about 13 MeV/u where the beam would be stripped and collimated to retain five charge states (73+ to 77+). These five charge states would then be accelerated to an energy of approximately 83 MeV/u where the beam would again be stripped and collimated to retain three charge states (87+ to 89+) that would be accelerated to the final energy of 400MeV/u. The optics design and simulation results for the two isochronous and achromatic charge-stripping sections are presented.

1 INTRODUCTION

The Rare Isotope Accelerator (RIA) [1] facility layout being evaluated at Michigan State University consists of three segments of SRF Linac separated by two charge-stripping sections [2]. The first two segments of RIA use Quarter-Wave and Half-wave Resonators with frequencies ranging from 80.5 MHz to 322 MHz, and the transverse focusing provided by superconducting solenoid magnets inside the cryostats. The last segment uses 805 MHz, 6-cell elliptical cavities, and room temperature quadrupole doublets for transverse focusing. The two charge-stripping sections provide a cost-effective method of achieving the final beam energy of ≥400 MeV/nucleon with the required beam power of ≥100 kW, and various design options were first investigated by ANL [3]. The requirements for these charge-stripping sections are:

- Transport the multi-charge ion beams after stripping to the following segment of RIA
- Provide adequate charge state separation for proper beam collimation
- Maintain beam longitudinal bunch length
- Minimize increase of the transverse beam emittances

For U^{238} beam, the 1st charge stripping will be at an energy of 12.87 MeV/u with a magnetic rigidity of 1.67 T-m. Five charge states (73+ ~ 77+) will be retained and transported to the following Linac segments. The 2nd charge stripping will be at 84.4 MeV/u with a magnetic rigidity of 3.63 T-m. Only three charge states (87+ ~ 89+) will be retained and transported to the following Linac segments. The assumed initial transverse beam emittance for RIA is 0.6 π mm-mrad (normalized). Included in the simulations is the significant emittance increase from multiple scattering in the stripping targets.

The design tools used in our studies are DIMAD [4], COSY INFINITY [5] and LANA [6]. The first two codes are used to perform the 1st and 2nd order system optics studies, higher-order aberration corrections, and particle tracking with high order maps. LANA is used for longitudinal beam dynamics simulations and 3-D particle tracking. The results show a very good agreement among these codes.

2 OPTICS

The layout of proposed optical system for the two charge-stripping sections for the RIA Driver Linac is shown in Figure 1. All three segments of RIA linac are assumed to be coaxial. The system has 4 identical cells with 4-fold symmetry. Each optical cell consists of a pair of reverse bending dipoles of -10° and +55° to achieve the isochronous condition for different charge states. An RF buncher in the center provides the longitudinal bunch length control as first proposed by ANL [3]. Two quadrupole triplets in each cell are used to achieve the achromatic conditions, both at the RF buncher location and the end of the system. The 1st order transfer matrix for both transverse planes is I, and the total system length is 36 m. Figure 2 shows the machine functions and beam envelopes for a transverse emittance of 0.6 π mm-mrad (normalized) for the 1st charge-stripping section.

Due to the high symmetry, the system has excellent 2nd order optical properties. No 2nd order geometric aberrations exist and there are only four 2nd order chromatic terms as shown in Table 1.

Table 1: 2nd Order Chromatic Aberrations

Term	Value
$X \mid X'\delta$	-24.8609
$X' \mid X\delta$	12.00843
$Y \mid Y'\delta$	-24.32289
$Y' \mid Y\delta$	21.35914

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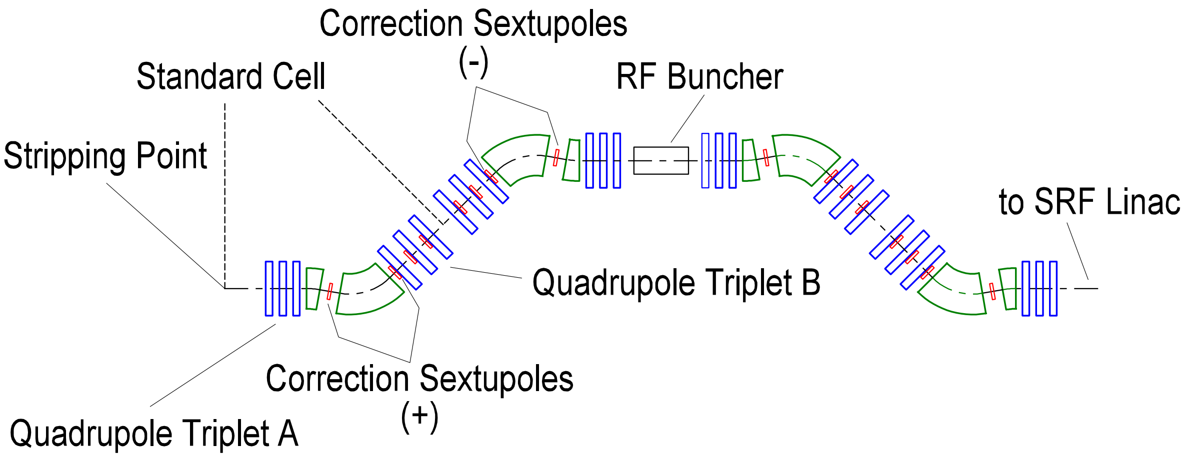

Figure 1: The layout of proposed optical system for the two charge-stripping sections of the RIA Driver Linac.

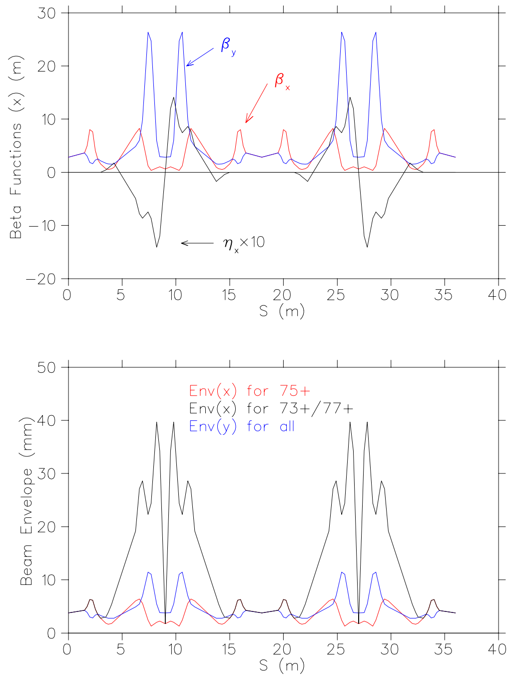

Figure 2: Machine functions and beam envelopes for the 1st charge-stripping section.

The system optical properties for the 1st charge-stripping section were evaluated by tracking 400 particles for each charge state uniformly populating the initial phase space through a 6th order map. Significant transverse beam emittance growth was observed, by a factor of 3.3 in horizontal plane, and by a factor of 1.8 in vertical plane, respectively, due to the dominant 2nd order chromatic aberrations shown in Table 1. These transverse beam emittance growths are not acceptable for RIA operation, and proper corrections are needed.

As shown in Figure 1, for each optical cell, 4 correction sextupole magnets are added to provide 2nd order chromatic corrections. Because of the asymmetry of the dispersion function, correction sextupole magnets have reverse polarities in neighboring cells. With correction sextupole magnets present, no 2nd order geometric aberrations are added, and all 2nd order chromatic aberrations are corrected. The system achieved a complete 2nd order achromatic condition. 3rd and higher order aberrations were compared with the previous values and only small perturbations observed. Particle tracking was again performed for different charge states through the corrected 6th order map for the 1st charge-stripping section. The results indicate that there is only about 10% emittance growth in the horizontal plane due to higher order aberrations and none in vertical plane. Similar particle tracking studies for the 2nd charge-stripping section show no observable beam emittance growths in either transverse plane.

3 THREE DIMENSIONAL BEAM SIMULATIONS

Longitudinal beam dynamics studies were performed using LANA. With the four pairs of reverse-bending dipoles in the optical system and symmetry of the dispersion function, the R_{56} of the 1st order transfer matrix is zero. This means there is no time difference for different charge states of the beam going through the system. However, the beam has an initial energy spread of about 0.4%, and the RF buncher used to maintain the beam bunch length will provide different energy gains for different charge states of the beam. This will result in a very small beam bunch length increase. The transverse de-focusing of the RF buncher is included in the simulation, and the lattice quadrupoles and sextupoles are readjusted to retain the 2nd order achromatic conditions.

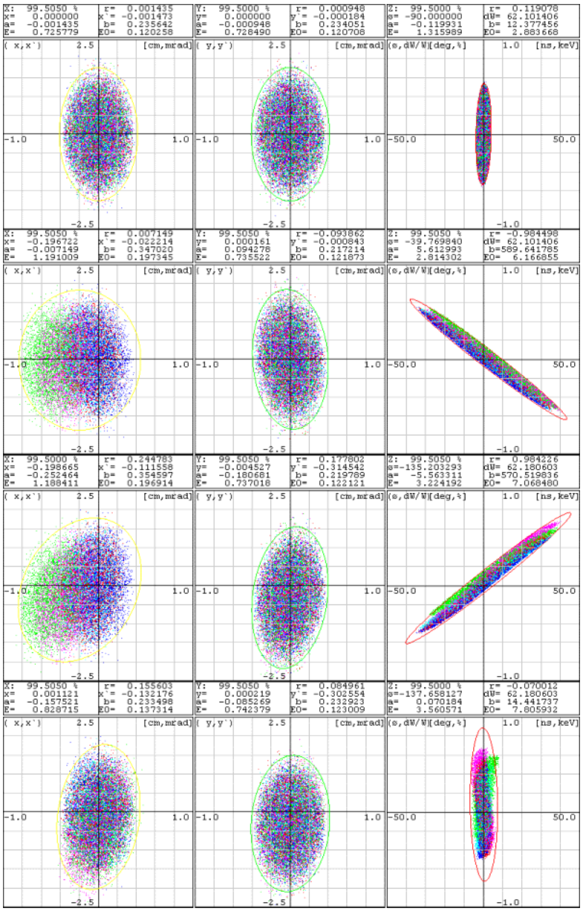

Figure 3: The 1st – 3rd column show the horizontal, vertical, and longitudinal phase spaces at the stripping foil, before and after the RF buncher, and at the end of the 1st charge-stripping section, respectively. Particle tracking was done using LANA.

Shown in Figure 3 are the tracking results by LANA that were in a very good agreement with the transverse plane results of DIMAD and COSY INFINITY. There was only about 10% horizontal emittance growth in the horizontal plane and none in the vertical plane. Some beam size increase in the RF buncher was observed for different charge states. However, the beam was still well inside the buncher aperture. The beam longitudinal bunch length is maintained within ±5° at the end of the 1st charge-stripping section, and only small differences exist for the five remaining charge states.

Similar 3-D particle tracking studies were performed for the 2nd charge-stripping section as well. No transverse beam emittance growth was observed in either transverse plane, and the beam longitudinal bunch length was maintained within ±10° at the end of the 2nd charge-stripping section.

4 HARDWARE

For the 1st charge-stripping section, the required quadrupole triplets have a radial aperture of 5 cm with lengths of 0.25m and 0.30m. The maximum pole tip field required was 6.8 kG. The sextupoles have the same radial aperture with a length of 0.1m and a maximum pole tip field of 1.39 kG. A single Quarter-Wave Resonator with frequency of 161 MHz and an accelerating gradient of 1.95MV/m can be used as the RF buncher.

For the 2nd charge-stripping section, the quadrupoles and sextupoles will have same length as for the 1st charge-stripping section. However, due to the higher beam energy and only three remaining charge states for the U^{238} beam, their radial aperture was reduced to 2.5 cm. The maximum pole tip field required for the quadrupoles is 7.4 kG and only 0.79 kG for the sextupoles. Four Half-Wave Resonator with frequency of 322 MHz and an accelerating gradient of 2.92MV/m can be used as the RF buncher.

5 CONCLUSIONS

A 4-cell magnetic system with 4-fold symmetry forming a complete 2nd order achromat is an excellent choice for the required charge-stripping sections for RIA Driver Linac. The system provides adequate charge separation with minimum transverse beam emittance growth. The longitudinal beam bunch length can be maintained using a reverse-bending isochronous section and RF buncher. The 3-D particle tracking simulation results show that the system performs very well under the RIA beam conditions. Further system optimization and beam simulations will be undertaken such as studying the impact of the misalignment and the mispowering error of lattice elements on the transverse beam emittance growth and proper longitudinal phase matching for the neighboring SRF Linac segments.

6 REFERENCES

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