BEAM DYNAMICS STUDIES AT NSCL OF THE RIA SUPERCONDUCTING DRIVER LINAC*

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Abstract

Extensive studies of the longitudinal and transverse beam dynamics have been done for the high power, cw superconducting linac for the proposed Rare Isotope Accelerator (RIA). The linac is to accelerate light and heavy ions to energies of ≥400 MeV/u with beam powers of 100 to 400 kW. For the heavier ions, simultaneous acceleration of several charge states will be used to meet the beam power requirement and to minimize the required accelerating voltage. The multi-charge state acceleration scheme does, however, present some challenges to the preservation of beam quality. A linac design with a beginning frequency of 80.5 MHz in lieu of a proposed design using 57.5 MHz was evaluated. The higher frequency option simplifies the geometry, decreases the number of different resonators types required, and reduces the microphonics problem. On the other hand, the higher frequency solution would require a somewhat larger number of accelerating structures. In both cases, superconducting solenoid magnets at the lower energies and room-temperature quadrupole doublets at the higher energies are used to provide the transverse focusing and beam matching. The performance characteristics of both scenarios were found to be similar. The results of the beam dynamics optimization are discussed as well as a comparative analysis of the two possible linac designs.

1 INTRODUCTION

Proposed as the next generation nuclear physics facility, RIA [1] will be capable of producing beams of nuclei far from stability. The RIA project is being studied at NSCL with the proposed layout given in Fig. 1. The RIA driver accelerator will be a superconducting, high power, cw linac [2,3]. The linac will consist of a room-temperature RFQ [4] and a number of super-conducting (SC) cavities.

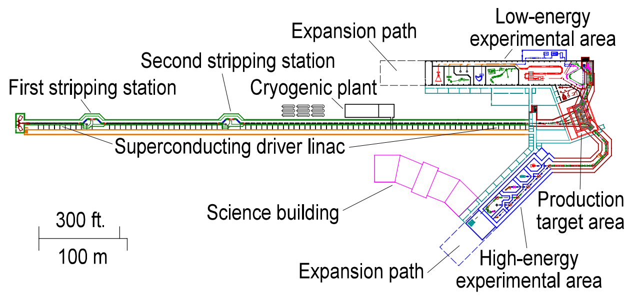

Figure 1: RIA facility layout. The driver linac extends from the ECR on the left to the Switch Yard in front of the Target Facility on the right.

The required linac voltage will be reduced by increasing the beam charge state at two charge-stripping sections dividing the linac into three segments. See Fig. 2.

The optimization of the number of cavity types and simplification of the geometry leads to a linac design consisting of four types of low- and medium-β structures with the frequencies 80.5, 161 and 322 MHz and three elliptical 805 MHz structures [5]. The increase of the starting frequency simplifies the cavity design but requires ~25% more units but with the same overall linac length when compared to the 57.5 MHz case.

The charge stripping takes place at 12.87-12.7 and 84.4-79.0 MeV/u respectively [6]. Three dimensional (3D) beam dynamic simulations were done using the LANA code [7]. The transverse periodical focusing system analysis was done with the DIMAD code [8].

The first low-β part of the Driver Linac between the RFQ and the first charge-stripping section uses Quarter-Wave Resonators (QWR) of three different optimum velocities with β=0.047, β=0.07 and β=0.14 at 80.5 (first two) and 161 MHz for the baseline multiple charge state beam $^{238}U^{28,29+}$ and energy range from 292 keV/u to 12.87 MeV/u.

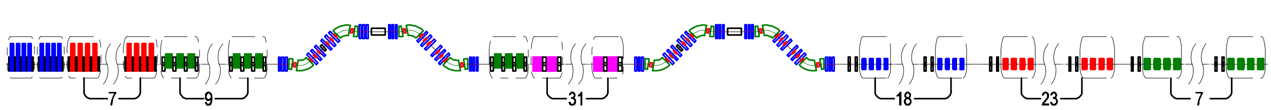

Figure 2: RIA driver linac layout. The linac consists of a RFQ and 602 superconducting cavities in 100 cryostats.

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The second medium-β part between the two stripping stations utilizes one additional type of cavity a Half-Wave Resonator (HWR) with β=0.28 at 322 MHz. The assumed multiple charge state baseline beam is $^{238}U^{73\text{-}77+}$ with energy from 12.7 to 84.4 MeV/u with anticipated equilibrium energy loss in the first stripper.

The third high-β part from the second charge-stripper to the end consists of the three different types of elliptical cavities with geometric β=0.47, β=0.61 and β=0.81 at 805 MHz. The beam $^{238}U^{87\text{-}89+}$ with energy from 79.0 to 400 MeV/u with corresponding energy loss in the stripping target was simulated. The last two elliptical cavities are identical to the SNS project design [9].

2 LONGITUDINAL BEAM DYNAMICS

One of the main challenges of the proposed driver linac for RIA is the simultaneous acceleration of several charge states [10].

The longitudinal beam dynamics impose special requirements on the configuration of the low energy part of the linac. The medium and high-energy parts do not limit the longitudinal acceptance significantly but require longitudinal matching after the stripping chicanes.

The longitudinal “focusing” technique was successfully applied to provide adequate multiple charge states matching in the low and medium-β part of the linac [3]. The cryostats in this part of the linac consist of 8-9 SC cavities and focusing solenoids.

A peak electric field of ~16.5 MV/m for the β<0.4 structures has been assumed. The first nine cryostats will have 8 SC cavities and five 10 cm (first two cryostats) and 20 cm (next seven) long solenoids placed at the beginning of the cryostat and after each pair of 80.5 MHz QWR of two different geometries. This lattice provides the necessary transverse focusing with sufficient longitudinal acceptance.

The next nine cryostats of the low-β and the first cryostat of the medium-β part have 9 QWR, 161 MHz, and four 40 cm long solenoids placed at the beginning of the cryostat and after each three SC cavities.

The rest of the medium-β part has 31 cryostat with 8 HWR and two 50 cm long solenoids after each four cavities.

The high-β part accommodates elliptical cavities grouped into cryostats with four cavities each. The suggested transverse focusing uses 50 cm long room-temperature quadrupoles in the inter-cryostats regions.

Fig. 3 shows the acceptances of the linac by parts with the corresponding longitudinal phase space portraits of the pilot uranium beam.

The 99% longitudinal emittance evolution along the linac including stripping chicanes is shown in Fig. 4. We can see that the 99% longitudinal emittance for every single charge state is approximately constant and the difference between charge states is negligible. The total emittance growth takes place only due to energy straggling and multiple charge states mismatch. The latter effect could be addressed by appropriate longitudinal matching of the beam at the stripper locations.

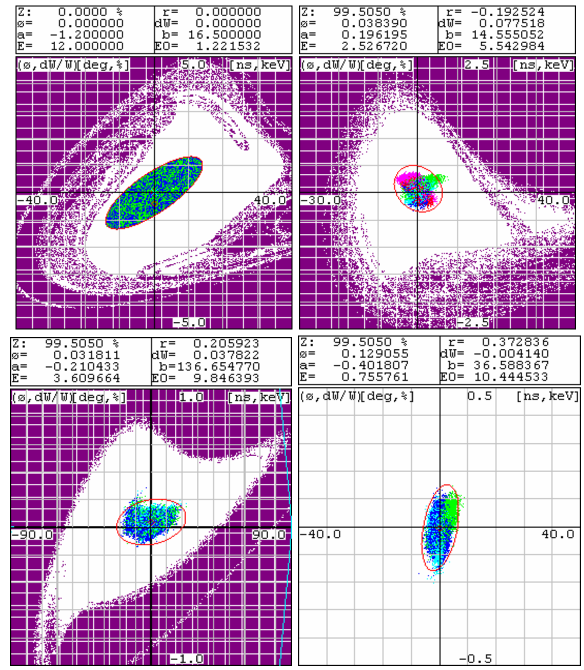

Figure 3: Longitudinal acceptances with corresponding emittances: low-β part with $^{238}U^{28,29+}$ at 292 keV/u (top left), medium-β with $^{238}U^{73\text{-}77+}$ at 12.7 MeV/u (top right), high-β with $^{238}U^{87\text{-}89+}$ at 79.0 MeV/u (bottom left) and final longitudinal phase space portrait at 400 MeV/u (bottom right).

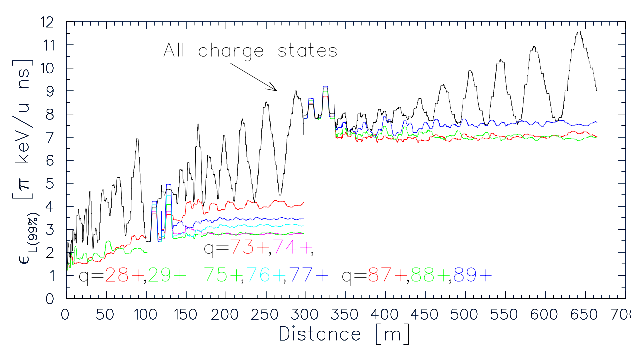

Figure 4: Longitudinal 99% emittances for separate (colors) and combined (black) charge states of ^{238}U beam along the RIA Driver linac.

3 TRANSVERSE BEAM DYNAMICS

Transverse focusing with superconducting solenoids is used for the low and medium-β parts of the linac. The superconducting solenoids can be situated inside the cryomodules, and require a minimum of extra space. The limitations on the longitudinal dimensions of the linac make this type of focusing the most effective for the low and medium energy. The total number of superconducting solenoids used in the simulations was 147. The length varied from 10 cm in the first two cryostats to 40 cm and 50 cm in the following modules.

All solenoids require a magnetic field of 9 Tesla or less. The transverse phase advance per focusing period σ_T is about 60° and is shown in Fig. 5. To match the beam envelopes, this parameter was adiabatically ramped at the beginning and at the end of sections with different transverse focusing periodicity.

Focusing with quadrupole doublets between cryostats (similar to those used for the SNS linac) was adopted for the high-β linac section. The total number of quadrupoles needed for this section is 98, with R_{BORE}=2.5 cm, total length of a single quadrupole L=25 cm, and field gradient G<56 T/m. A comparison of the DIMAD [8] beta function calculation and LANA [7] particle tracking results gave excellent agreement.

Fig. 6 shows the transverse emittance evolution along the linac. The multiple charge state rms and 99% emittances grow only at the end of the low-β part due to the QWR beam steering and at the stripping locations due to the mutilpe scattering.

The overall maximal beam envelope for different charge states separately as well as for total multiple charge states beam is shown in Fig. 7 and is well within the accelerator aperture.

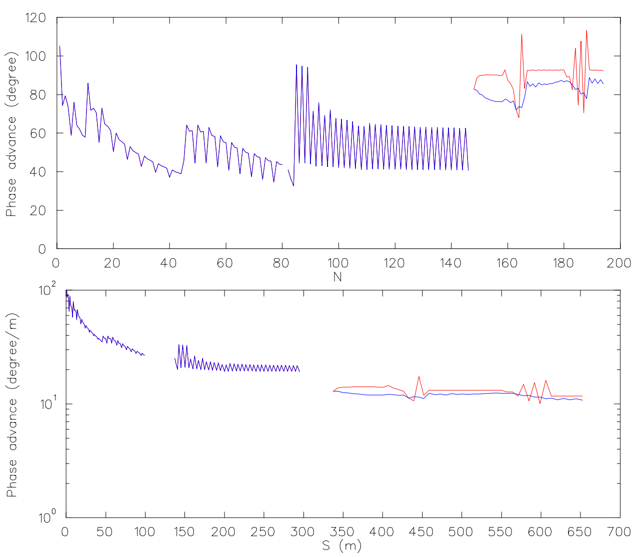

Figure 5: Transverse focusing phase advance per period (top) and per real estate (bottom) for the reference charge states of ^{238}U beam along the RIA Driver linac; red for σ_x and blue for σ_y in the high-β section.

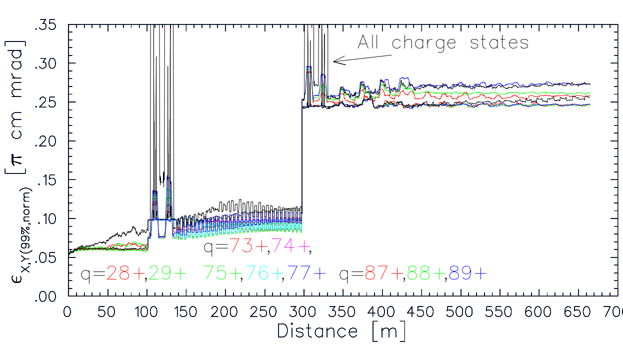

Figure 6: Transverse 99% emittances for all simulated charge states of ^{238}U along the driver linac.

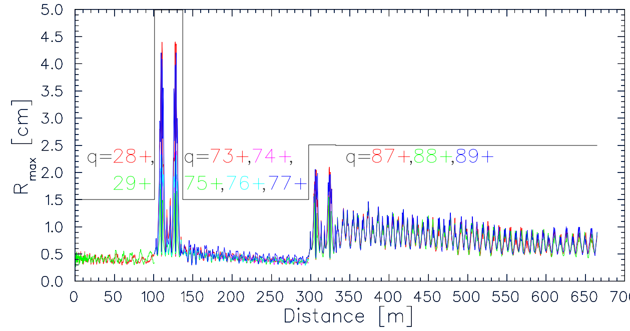

Figure 7: Maximal transverse envelops for all simulated charge states of ^{238}U along the driver linac; the aperture of the respective superconducting cavities and quadrupoles (for high-β part) is also shown.

4 CONCLUSION

A new strategy for optimization of the multiple charge state longitudinal beam dynamics in the low-β superconducting linac has been proposed. A procedure for 3D matching of the different superconducting linac subsections has been developed and successfully applied to a specific driver linac layout.

Simulations of misalignment and rf error in the driver linac components are underway and will be used to determine the tolerances and layout of the steering elements.

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