A HIGH-CHARGE-STATE ACCELERATION SCHEME FOR POTENTIAL UPGRADE OF THE HRIBF

Y. Zhang,* G. D. Alton
Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831-6368, USA

Abstract

This article describes a high-charge-state linear post accelerator for enhancing the number and intensities of short-lived radioactive nuclei at the Holifield Radioactive Ion Beam facility (HRIBF). The system consists of a room temperature RFQ, a normal conducting IH linac and a SC QWR linac that is designed to either bypass or post accelerate beams from the 25-MV tandem. The voltage gain of the linac system will reach 60 MV making possible the acceleration of ions with masses, $M \leq 150$, above the Coulomb barrier. Since the linac accelerates positive-ion beams, it will increase the number of elements that can be delivered for research by a factor of ~ 3 and the intensity of a given species by orders of magnitude over those of the present HRIBF.

1 INTRODUCTION

The Holifield Radioactive Ion Beam Facility [1], completed in 1997, is the first ISOL-based RIB facility in America. It consists of the following major components: the k = 100 Oak Ridge Isochronous Cyclotron, an Isotope-Separator-On-Line and the 25-MV URC tandem accelerator. Although the tandem is a highly reliable post-accelerator, the species are limited to those that can be efficiently produced in negative ion form, either directly or indirectly. Since the majority of the elements have electron affinities less than 1 eV, most beams must be generated by charge exchange. The process degrades RIBs by inducing energy spreads of a few hundred eV during collisions with the exchange vapor, and therefore, compromises the ability to remove isobaric contaminants with conventional magnetic systems. Although the ORIC, built in 1962, has a k = 100 rating, in practice, it operates at $k \cong 42$ for proton beams because of RF tuning and radial focusing limitations. Thus, production of short-lived species is greatly restricted because of the limited intensities and energies available with ORIC beams. The high-intensity linac driver, designed as a replacement for the ORIC, can accelerate proton beams to 200 MeV with intensities up to 200 μA, corresponding to a beam power of ~ 2 orders of magnitude higher than those from the ORIC. LNL has chosen a positive-ion injector [2] and ANL has proposed a next generation RIB facility, RIA [3] based on the acceleration and fragmentation of high-energy heavy-ion beams.

As discussed previously, the 25-MV URC tandem accelerator limits the number and intensities of most RIB species because of the necessity of having to inject negative-ion beams, most of which must be formed through charge exchange of initially positive-ion beams. The charge-exchange process, not only compromises beam quality, but also reduces the efficiency of RIB generation. For a typical case for which the efficiency for both positive- and negative-ion formation is 10%, the overall efficiency is reduced to 1%. RIB beam intensities are further reduced by the use of gas or C- foil strippers in the terminal of the tandem, resulting in transmission losses. (The transmission efficiency for a gas stripper is ~20% while that of a C-foil stripper is ~8%, in the 25-MV tandem.) Thus, for the example cited, the RIB intensity for the gas stripping scenario would be reduced to 0.2% and to ~0.08% for a C-foil stripper. The proposed high-charge-state linac system is predicated on the use of a multi-charge-state ECR ion source that can generate beams of noble gas elements such as $^{40}Ar^{9+}$ and $^{84}Kr^{14+}$ and volatile metals such as In^{20+} at >10% efficiency. Thus, the efficiencies for the high-charge-state linac system would be amplified by factors, of ~125 and ~50 over those for the existing tandem accelerator based HRIBF system. In the advent that the charge-state breeding concept ($A^{1+} \rightarrow A^{q+}$) must be utilized in order to protect radiation sensitive permanent magnets in ECR ion sources from degradation, the overall efficiency would decrease to ~1% for the high-charge-state acceleration scheme. Thus, the efficiency would still be 12.5 to 5 times higher than either of the tandem stripper scenarios. (The breeder method is being developed for use at high-charge-state accelerator RIB facilities such as SPIRAL at GANIL [4].)

A description of the high-intensity light-ion linear driver accelerator can be found in a technology report [5], and will not be included in this paper. In the conceptual design studies for the linear accelerator, the codes, TRACE3D [6], LYRAN [7], PARMILA [8], and the electromagnet code SUPERFISH [9] were used to design components of the high charge-state linac system and RFQ codes such as PARMTEQ [10] were used to simulate transport through the RFQ. A low-charge-state heavy-ion linear accelerator system, designed as an alternate candidate system for upgrading the HRIBF, is also described in these proceedings [11].

2 SCOPE OF THE LINAC

Fig. 1 schematically represents the proposed high-charge-state linac system while the elements of the system and their performance parameters are listed in Table 1. In addition to the high-intensity linac driver, the energy booster for the HRIBF will consist of a high-charge-state ECR ion source, a normal conducting RFQ, four NC Inter-

* China Institute of Atomic Energy, Beijing, China.

Digital H type resonators (IH cavities) and a SC QWR linac system. RIBs from the ECR ion source are passed through a first stage M/q analyzer, accelerated from the high voltage platform through an isobar separator (mass resolution: M/ΔM = 20000) before injection into the 100-MHz NC RFQ. Normal conducting IH cavities are chosen as the acceleration structures between the RFQ and the SC QWR linac, since they have very high acceleration efficiencies in the output velocity range of the RFQ, ($0.02 \geq \beta \geq 0.05$). The combined voltage gain of the room temperature components of the post accelerator system (i.e., ECR, RFQ, and IH linac) is 7.5 MV. The output energies for heavy ions from the room temperature system are equivalent to those from a 13MV tandem.

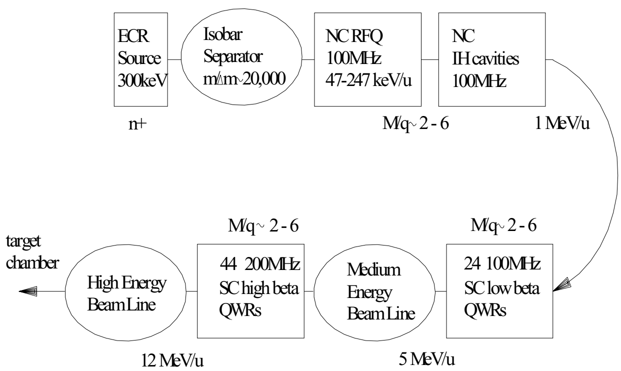

Fig. 1. Schematic diagram for acceleration of high-charge-state RIBs.

The SC linac booster is the best choice for accelerating RIBs to their final energies because SC cavities operate reliably at high field gradients in CW mode at reduced cost. In addition, the independently phased Quarter-Wave-Resonators have a very broad velocity profile so that the energies of RIBs can be varied over a wide range. The normal conducting RFQ, NC IH linac, and low beta SC linac sections, operate at 100 MHz and have a combined voltage gain of ~25MV. The high beta SC QWR linac section operates at a resonant frequency of 200 MHz and has a voltage gain of ~35 MV.

Table 1. Acceleration elements of the new HRIBF

Element	Beta (v/c)	F (MHz)	Num.	Type	Gain (MV)
ECR	0-0.009		1	NC	0.3
RFQ	– 0.023	100	1	NC	1.2
IH	– 0.051	100	4	NC	6
QWR	– 0.104*	100	24	SC	18
QWR	– 0.160*	200	44	SC	35

*Mass-to-charge ratio about 5

3 NORMAL CONDUCTING RFQ

The charge-to-mass ratio is a key parameter for the design of a heavy-ion RFQ. The high-charge-state ECR ion source [12] is assumed to produce beams with mass-to-charge, (M/q) ratios within the range of 2 to 6. Since the injector has a maximum voltage of 300 kV, the RFQ is designed to accept beams with energies of ~46.7 keV/u and to accelerate them to an output energy of ~247 keV/u. The normal conducting RFQ has a voltage gain of 1.2 MV and serves mainly as an adiabatic beam buncher that captures, focuses, and accelerates ~90% of injected DC beams. Since intensity is at a premium at any RIB facility, the high bunching efficiency attribute of the RFQ is an added bonus of the heavy-ion linac post-accelerator concept.

Table 2. Design parameters of the RFQ

Frequency	100 MHz
Number of cells	193
Vane length	377 cm
Minimum aperture radius	3.0 mm
Peak vane voltage	78 kV
Peak surface electric field	2.0 Ek
RF power	62 kW
Input beam	46.7 keV/u (β=0.010)
Output beam	247 keV/u (β=0.023)

The RFQ operates at a resonant frequency of 100 MHz and has a normalized transverse acceptance of ~1.0 π·mm·mrad. It is housed in a cavity of length: ~4 m, and inner diameter: ~45 cm. For practical CW operation, the maximum inter-vane voltage will be 78 kV, and the RF power dissipated on the entire RFQ structure, ~60 kW. The apertures in the last four cells of the RFQ will be increased to reduce radial focusing and lower the maximum magnetic gradient as required to optimally match into the following IH cavities and quadruple structures. The design parameters of the RFQ are listed in Table 2, while Fig. 2 shows the beam transport results obtained with PARMTEQ.

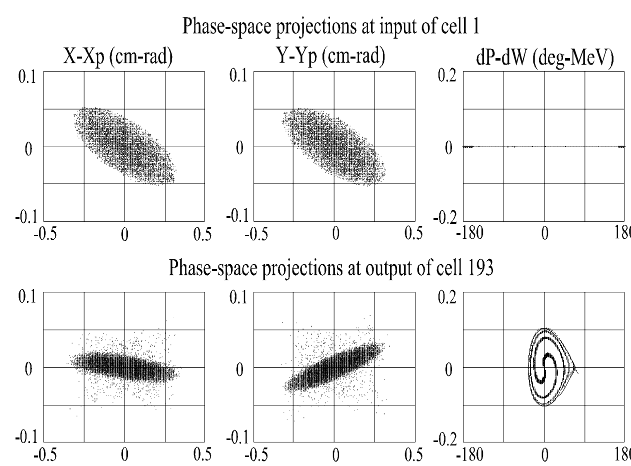

Fig. 2: Phase-space projections of beams injected into and exiting from the RFQ.

4 NC IH CAVITIES

Room temperature Inter-digital H type resonators (IH cavities) were chosen for acceleration of beams from the RFQ because of their high acceleration efficiencies [13, 14] in the velocity range, $0.02 \geq \beta \geq 0.05$. Four 100 MHz IH cavity tanks are required to accelerate ions for injection into the super-conducting QWR linac. These structures are practical for CW operation since the RF power dissipated in the walls of each IH tank is less than 20 kW. The four tanks are independently phased and beams from the RFQ can be efficiently captured, accelerated, and injected into the following SC linac. The design parameters for the IH cavities are: injection velocity, $\beta = 0.023$; output velocity, $\beta = 0.051$; voltage gain, 6 MV; total electrode length, ~3m; tank diameter, ~70cm. Since the inter-tank distances need to be short in order to reduce longitudinal mismatching, magnetic quadruple doublet lenses with high gradients will be installed between each IH tank to provide strong transverse focusing; this distance can be made as short as 30 cm. Fig. 3 displays the results of simulation studies obtained by use of the TRACE3D.

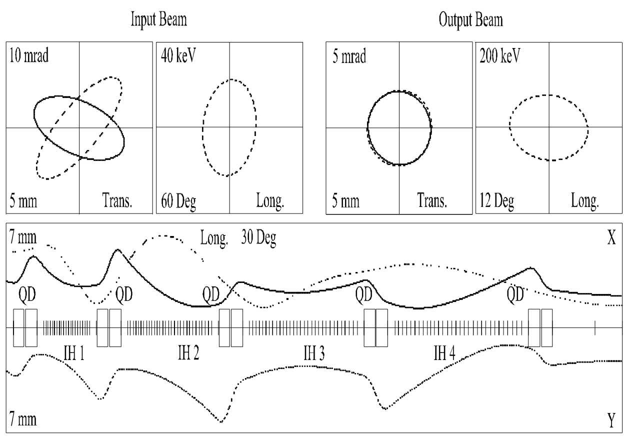

Fig. 3: Beam envelope through the IH linac

5 SC LINAC PERFORMANCE

Acceleration and transport of heavy ions in the post accelerator are simulated with several codes introduced previously and details of the SC linac described in Ref. 11. These studies show that the new linac system is capable of accelerating intermediate mass ions such as $M \cong 85$ to 12 MeV/u, assuming a M/q ratio of 5 and heavy ions with $M \leq 150$ to 10 MeV/u that have M/q ratios of 6. Simulation results of the SC linac are listed in Table 3.

Table 3. Beam simulation results

Ion	O^{+8}	Ar^{+13}	Ni^{+15}	Ge^{+1}	Kr^{+17}	Xe^{+2}
				5		7
E_{in}	19.2	47.9	70.3	88.6	100	158
MeV/u	1.2	1.2	1.2	1.2	1.2	1.2
β_{mid}^*	0.14	0.12	0.11	0.10	0.10	0.10
	1	1	2	4	3	1
E_{mid}^*	149	276	343	368	419	635
MeV/q	19	21	23	25	25	24
β_{out}	0.23	0.19	0.17	0.16	0.16	0.15
	2	6	7	1	0	9
E_{out}	417	745	879	900	1021	1592
MeV/u	26.0	18.4	14.9	12.2	12.2	12.0
MeV/q	52.1	56.5	58.6	60.0	60.1	59.0

*Output of the low beta SC section; units of energy: MeV

6 CONCLUSIONS

According to the conceptual design studies described in this report, the high-charge-state post-acceleration system and combination of the 200-MeV high intensity proton linear driver accelerator will significantly enhance the research capabilities of the HRIBF. The system can optimally accelerate ions with mass-to-charge ratios, M/q = 5 or 6 to energies up to ~60MeVq. The modular aspects of the design make construction of the project in stages very appealing whenever budgetary restrictions preclude construction of the full energy complement. However, if the project is divided into stages, the room temperature components (ECR ion source, RFQ and the 4-tank NC-IH system) should be built as an integral stand-alone acceleration system since this combination has a voltage gain sufficiently high (~7 MV) to perform nuclear astrophysics research ($E \geq 1$ MeV/u) with species up to mass, M = 150. Studies directed toward further optimization of the HRIBF upgrade acceleration system in terms of simplicity, efficiency, ease of operation and cost of the facility continue.

ACKNOWLEDGEMENTS

Research sponsored by Oak Ridge National Laboratory, managed by UT-Battelle, LLC, for the U.S. Department of Energy under contract number DE-AC05-00OR22725. The authors would like to thank Dr. V. Palmieri and Dr. A. Porcellato of LNL, Dr. S. Takeuchi of JAERI, and Prof. W. Jiang of CIAE for providing information.

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