HEAVY-ION BEAM DYNAMICS IN THE RIA POST-ACCELERATOR*

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Abstract

The RIA post-accelerator (RIB) includes three main sections: a room temperature injector with design ion charge-to-mass ratio 1/240 and output energy of ~93 keV/u, a superconducting (SC) linac for ions with charge-to-mass ratio 1/66 or higher up to an energy of ~1 MeV/u and a higher energy SC linac including existing ATLAS to produce 10 MeV/u beams up to uranium. Two strippers are installed between the sections. Extensive accelerator design studies and end-to-end beam dynamics simulations have been performed to minimize the cost of the linac while providing high-quality and high-intensity radioactive beams. Specifically, we have found that cost-effective acceleration in the front end can be provided by several hybrid RFQs proposed and developed for acceleration of low-velocity heavy ions. For beam focusing in the second section it is appropriate to use electrostatic lenses and SC quadrupoles inside common cryostats with the resonators.

INTRODUCTION

The RIA post-accelerator is a complex system that includes many different accelerating structures and focusing elements operating both at room and cryogenic temperatures. It is designed for acceleration of a wide variety of radioactive ions starting from the lowest possible charge-to-mass ratio. The reference design [1] of the injector section of the post-accelerator includes a 380 kV open-air variable-voltage platform which carries a multi-harmonic buncher, the first two sections of 12 MHz RFQ, and two helium gas stripper cells. The pre-ATLAS superconducting section of the RIB linac includes 4 types of cavities designed for different geometrical beta and operating at 4th, 6th and 8th harmonics of the 12.125 MHz fundamental frequency. In the SC linac-1 (see Fig. 1) cavities will be installed in 6 cryomodules each with the length of ~6 m. Each cavity can provide ~1 MV of accelerating voltage in the velocity range $0.011c \le v \le 0.06c$. In the reference design focusing along SC linac is provided by 15 Tesla SC solenoids following every cavity [1].

The reference design satisfies all specifications of the RIB linac but requires a large number of expensive high field SC solenoids. Therefore we have investigated alternative designs. A design based on Alternating Phase Focusing (APF) has been discussed in ref. [2]. In a SC linac, APF can be effectively applied for focusing of low velocity ($v \le 0.02c$) ions. A focusing structure based on combination of APF and reduced number of SC solenoids, so called Combined Focusing Structure (CFS) [3], can be applied in the SC linac-1. The APF and CFS can significantly reduce the cost of the RIB linac. The CFS option maintains beam quality along the linac but still requires reduced number of ~14 Tesla SC solenoids compared to the baseline design.

The objectives of this paper are to further modify the RIB accelerator design to minimize its cost while providing high-quality and high-intensity radioactive beams.

LINAC LAYOUT

Normal conducting front end

Simplified block-diagram of the RIB linac layout with the modified front end is shown in Fig. 1. As compared to the reference design we propose to reduce radioactive ion source voltage to 60 kV, HV platform voltage to less than 36 kV and inject ions into the RFQ with initial energy of 0.4 keV/u. The latter is entirely possible due to the low operating frequency of the RFQ which results in an accelerating cell length of ~11.5 mm in the RFQ entrance.

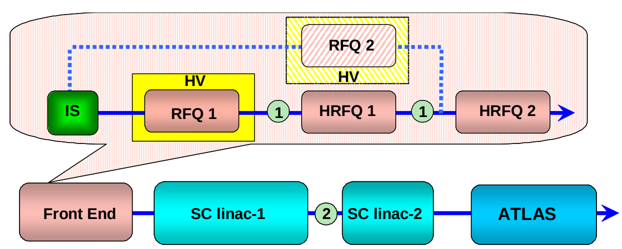

Figure 1: Simplified layout of the RIB Linac. 1 – gas strippers, 2 – carbon stripper, HV–high voltage platform.

Ions with charge-to-mass ratio in the range $1/240 \le q/A \le 1/66$ will be accelerated by a conventional RFQ-1 and hybrid RFQ-1 (HRFQ-1) [4] operating at 12.125 MHz (see Fig. 1). The hybrid RFQ structure is slightly modified compared to the originally developed HRFQ [4]. In the new design, the FODO focusing lattice comprising rf quadrupoles with the length $\beta\lambda/2$ located between every four accelerating gaps forms the hybrid RFQ structure.

The main parameters of the RFQ-1 and HRFQ-1 are listed in Table 1. The platform potential U_{HV} is adjustable within the range $-33kV \le U_{HV} \le 36$ kV to equalize RFQ injection velocity for all ion species. The proposed RFQ structure can provide acceleration of ions with q/A higher than 1/66. However, this regime requires very low power in the resonators and may cause problems in maintaining a stable accelerating voltage. A bypass beam line is proposed as shown in Figure 1. The latter can be considered as an upgrade option. In the bypass beam-line, the injection energy can be higher due to higher q/A and

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Table 1: RFQ parameters

Parameter	RFQ-1	HRFQ-1
Ion energy in/out, keV/u	0.4/7.4	7.4/24.4
Average radius, mm	6.5	12
Inter-vane voltage, kV	68	130
Peak surface field, kV/cm	135	135
Transverse acceptance, π·mm·mrad	0.3	0.6
Phase advance σ_T, deg	25	55

equals to 1.6 keV/u. Acceleration up to 24.4 keV/u is provided by a conventional RFQ operating at 24.25 MHz. Due to the fact that RFQ focusing is scaled as $A\lambda^2/q$, where λ is the rf wavelength, the RFQs on both beam-lines can be designed with the same average distance between opposite electrodes and inter-electrode voltage. Ion beams from both lines are transported to the HRFQ-2 operating at 24.25 MHz and are accelerated up to 92.7 keV/u.

Superconducting linac

In the modified design of the RIB linac the focusing in the SC section is provided by quadrupole lenses with the effective length 26 cm and focusing gradients less than 80 T/m. The focusing lattice has been designed to provide constant beam size along the SC linac. SC quadrupoles with parameters close to the RIA post-accelerator specifications have been developed and reported recently [5,6]. Low beam velocity in the first cryostat facilitates the use of electrostatic focusing quadrupoles with inter-electrode voltage <30 kV.

BEAM DYNAMICS

Bean dynamics in the RIB linac was simulated for uranium ions with initial charge-to-mass ratio q/A=1/240. The latter is changed to q/A=4/240 after the gas stripper and to q/A=37/240 after the carbon stripper. The initial normalized transverse emittance containing 95% of particles ε_t=0.05 π·mm·mrad is defined by the acceptance of the high-resolution isobar separator located upstream of the accelerating structures. Generally, beams with initial emittance ~0.2 π·mm·mrad can be accelerated with 100% transmission in the proposed linac.

Prior to the beam dynamics simulations a careful matching of beam Twiss parameters in various sections of the linac has been provided. For this purpose the codes TRACE3D [7] and TRACK [8] have been applied. An optimization routine was developed for the TRACK code and it was used for the final matching in realistic 3D fields in all accelerator elements. End to end beam dynamics simulations in the modified RIB linac have been also performed with the same code. Three-dimensional fields of all linac elements for the TRACK code have been obtained from the external codes EMS and MWS [9]. $2\cdot10^5$ charged particles have been tracked through the whole linac including all matching transport lines and strippers.

The longitudinal emittance of heavy ion beam is formed by two-stage bunching. The first stage is a buncher operating at 12.125 MHz and located upstream of the RFQ-1. This buncher forms a ~100^0-120^0 bunch containing ~90% of particles at the RFQ-1 entrance (see Fig. 2A). Additional bunching as a 90^0 bunch rotation takes place in the first 30 cells of the RFQ and more than 90% of particles are transformed into $\pm25^0$ phase width as seen in Fig. 2B. Dashed line in Fig. 2B represents the separatrix at the beginning of the acceleration section in the RFQ-1. Two-stage bunching provides 90% capture efficiency and forms very low longitudinal emittance. The phase space plot at the RFQ-1 exit is shown in Fig. 3A. The rms emittance is $4\varepsilon_{l\ rms}$=0.057 π·kev/u-nsec. The emittance containing 95% of accelerated particles is $\varepsilon_{l95\%}$=0.082 π·kev/u-nsec.

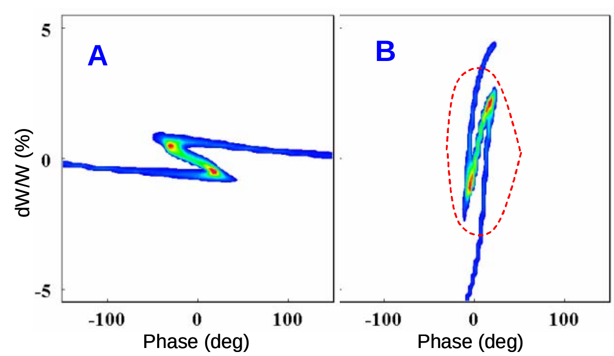

Figure 2: Phase space plots in the longitudinal plane during two stage bunching. **A** –at the RFQ entrance, **B** – at the exit of RFQ internal buncher.

Both Hybrid RFQs have been designed to preserve low longitudinal and transverse emittances. The emittance growth in these sections does not exceed 15%. The longitudinal phase space plots along the front end structures are presented in Fig. 3.

Superconducting cavities offer much higher accelerating gradients than NC structures. If one likes to use full level of available gradients, there are two main consequences, especially in the first cryostat where particle velocity is low:

- Strong dependence of the accelerating field on radial coordinate;
- Large phase slippage of the bunch center with respect to the rf field due to the fixed geometry of the SC cavities.

These effects can result in both transverse and longitudinal emittance growth [10]. As was discussed in ref. [10], the emittance growth can be completely avoided by using strong transverse focusing with 90° phase advance over the focusing period which includes a resonator and strong SC focusing triplet. It was found that the triplets can be replaced by more economic 15-Tesla solenoids [1]. The effect of emittance growth can be significantly suppressed by increasing transition energy from the NC to SC sections of the RIB linac. A cost-

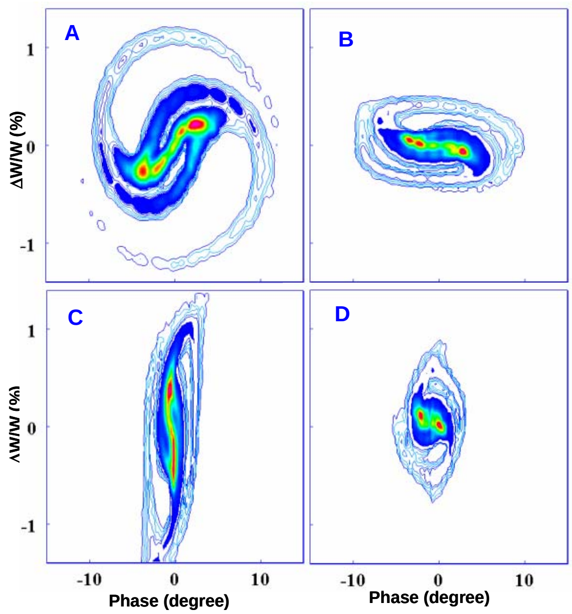

Figure 3: Phase space plots in the longitudinal plane along the front end structures: RFQ output (A), HRFQ-1 output (B), HRFQ-2 entrance (C) and HRFQ-2 output (D).

effective strong focusing in the first cryostat can be obtained by using electrostatic FODO focusing structure. The simulations have shown that the rms emittance growth in both longitudinal and transverse planes does not exceed 4% in the first cryostat with the proposed modifications (Fig. 4). The FODO focusing provided by SC quadrupole singlet is used in all other cryostats.

Figure 5 shows evolution of transverse and longitudinal emittances along the SC linac prior to the carbon stripper. The short inter-cryostat space allows us to achieve good matching of transverse motion by adjusting gradients of outermost quadrupoles therefore the transverse emittance growth is negligible. However the inter-cryostat spaces are the main source of mismatching in the longitudinal plane that results in relatively small but continuous longitudinal emittance growth up to ~36% which can be avoided if the cavities are operated at larger phase angle, for example, -30°.

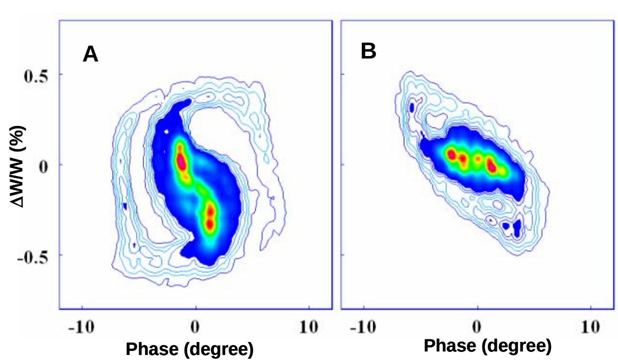

Figure 4: Phase space plots in the longitudinal plane before (A) and after the cryostat #1 (B).

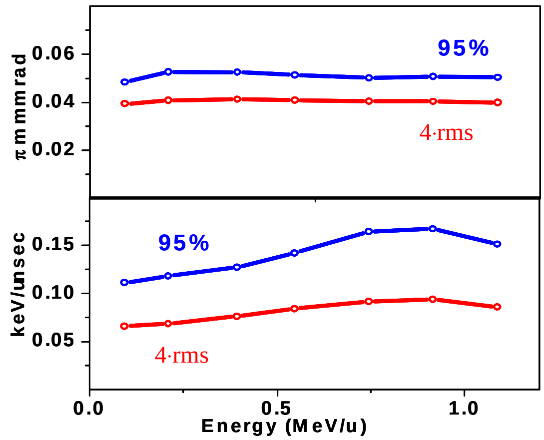

Figure 5: Evolution of transverse (A) and longitudinal (B) emittances upstream of the carbon stripper.

CONCLUSION

The design of the RIA post-accelerator has been modified to provide high quality beams at reduced cost. The injection energy into the RFQ has been reduced to lower the potential of the HV platform. Two-stage bunching provides 90% capture efficiency of the dc beam and formation of extremely low longitudinal emittance at the RFQ output. A new version of hybrid RFQ structure has been developed to increase total acceleration efficiency of the front end preserving low beam emittances. In addition, the new HRFQ provides higher injection energy into the SC linac. The focusing lattice in the SC section of the RIB linac has been optimized to incorporate cost-effective electrostatic and SC quadrupole magnets. An extensive overall beam dynamics optimization and development of effective accelerating structures has been carried out to produce high-quality radioactive beams in a cost-effective manner.

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