HEAVY-ION BEAM DYNAMICS IN THE RARE ISOTOPE ACCELERATOR FACILITY *

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Abstract

Recently the possibility of simulteniously accelerating particles with a range of charge-to-mass ratios (~20%) to the same energy was proposed and demonstrated for a superconducting (SC) linac [1]. This development has two immediate applications: 1) acceleration of heavy ions that are limited by ion-source intensities in a high-power medium energy linac such as the driver linac for the proposed Rare-Isotope Accelerator (RIA) Facility and 2) substantial intensity enhancement of secondary radioactive beams in post-accelerators.

ACCELERATION OF MULTIPLE-CHARGE STATE HEAVY-ION BEAMS

The concept of multiple charge state (multi-q) beam acceleration can enhance the utility of high-intensity linacs for heavy ions where the ions may have to be stripped repeatedly to make optimal use of the accelerating voltage. Such linacs are being considered for major facilities for nuclear physics research [2]. For example, accelerating ^{238}U to 400 MeV/u will require two or three stages of stripping. If only one charge state were accepted after each stripping, the intensity at each stage would be reduced by a factor of ~5 and the maximum beam power would be available ≈4.6 kW with present ion source performance. A scheme where essentially all the charge states can be accelerated delivers ~80% of the beam thus providing up 56 kW at the desired final energy. In addition, it was shown that the front end of a SC linac can be designed to accept two charge states of heavy-ion beam from the ECR ion source, doubling the available beam power [3].

A comprehensive study of multi-q beam dynamics in SC linacs has been reported in ref. [4]. The simultaneous acceleration of neighboring charge states becomes possible because the high charge-to-mass ratio makes the required phase offsets of the synchronous particles small:

$$\varphi_{s,q_i} = -arccos\left[\frac{q_0}{q_i} \times cos\,\varphi_{s,q_0}\right], \qquad (1)$$

where q_0 is the reference charge state with corresponding synchronous phase $\varphi_{s,q0}$, the sub-index i corresponds to the neighboring charge state with the same mass number A. For the best matching, bunches with different charge states must be injected into the linac at slightly different rf phases. The higher the charge state, the sooner it must arrive at the SC resonator to be matched. For most applications, relatively few charge states need to be accelerated simultaneously. Therefore the differences in the matched synchronous phases are just a few degrees and time matching system is not necessary. If all charge states are injected at the same time (at the same rf phase), then each charge state bunch will perform coherent synchrotron oscillations with respect to q_0. One can view this as an increase in the effective longitudinal emittance of the total beam, relative to the (partial) longitudinal emittance of the individual charge state bunches.

The spread in charge states that can be accepted for acceleration depends primarily on the extent that the focusing system can limit emittance growth in transverse phase space. In high intensity linacs, the tolerable emittance growth is set by the intensity of lost energetic ions that can produce residual activation of the accelerator components. Therefore, in heavy-ion linacs at low intensity or low energy, a wide range of Δq/q, about ±10%, can be accepted and accelerated. However in high intensity (~10^{13} ions/s) and medium energy (~400 MeV/u) machines, the tolerable spread of charge states is lower, ~±3 %. In radioactive linacs the limitation for the range of Δq/q is imposed by an acceptable beam quality.

Standard periodic focusing theory can be used to analyze the simultaneous acceleration of the several charge states. Our studies show that effective transverse emittance growth of multi-q beams is caused by slightly mismatched conditions for different charge states in the periodic focusing channel and misaligned focusing elements. This effect restricts the tolerable charge spread in the linac.

A test of this concept with uranium beams was performed at the 50 MV SC linear accelerator at Argonne National Laboratory (the ATLAS accelerator). Uranium ions, stripped in a foil, with 8 charge states (Δq/q ≈20%) have been accelerated through a portion of the ATLAS linac from 286 MeV to 690 MeV, with 94% of the injected uranium in the accelerated beam. Emittance of the resultant beam has been measured and the energy spread was 1.3% compared to 0.4% for a single charge state [1]. As is shown in this paper multi-q beam parameters can be significantly improved by careful design of the accelerator components.

THE RIA DRIVER LINAC

The RIA is being considered as a major nuclear science facility for the near future. A cw SC 1.4 GV driver linac and 120 MV post-accelerator are being designed for the RIA Facility. A conceptual design of the driver linac has been developed (see, for example, [5,6]), the major elements of which are shown in Fig. 1. Except for the injector radio frequency quadrupole (RFQ), the entire linac is based on SC accelerating structures. The "baseline" driver linac design consists of ~400 SC cavities

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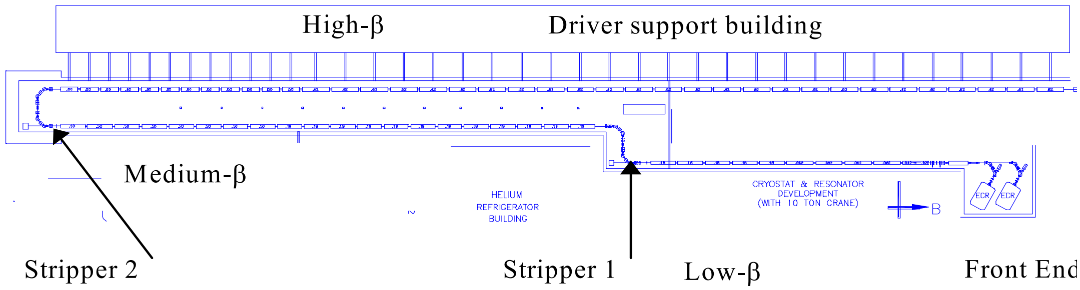

Figure 1: Elements of the proposed RIA driver linac.

of 9 different types. The majority of the cavities (98%) fall into 7 different types. Recently we have developed a variation of the driver linac based on triple-spoke SC resonators being designed at ANL [5]. This option reduces total number of cavities to ~350 with fewer types of the SC resonators.

The driver linac can be tuned to provide a uranium beam at an energy of 400 MeV/u and can be re-tuned to provide a proton beam at 900 MeV. To obtain 400 MeV/u uranium beams the driver linac uses two strippers. Three different sections of the linac are demarked by the charge-strippers. The low-β section of the linac is that portion prior to the first stripper, the medium-β section is between the two strippers, and the high-β section is that portion following the second stripper. The low-β section includes a front end with the possibility to accept for acceleration two charge states simultaneously and a SC linac up to ~10 MeV/u for uranium. The medium-β and high-β sections are designed for acceleration of multi-q beams. After each stripper, there is a magnetic transport system (MTS) [7] which provides six-dimensional matching of multiple-q beams into the following accelerating structure. In addition, the MTS is designed to separate and dump the low-intensity unwanted charge states in order to avoid beam losses in the high-energy section of the driver linac.

The driver linac is a high intensity machine and relative beam losses in the high-energy section must be kept below 10^{-4}. Acceleration of multi-q uranium beams places stringent requirements on the linac design. Any other lighter ion beam with much smaller emittances can be accelerated with no losses. End-to-end beam dynamics simulations in six-dimensional phase space have been applied to study all possible sources of beam halo formation and possible beam loss in the driver linac. Major contributors to the effective emittance growth were identified as: a) multiplicity of charge states; b) passage through the stripping foils and c) random errors of rf fields and misalignments of focusing elements. We have developed the concept of a "beam-loss-free" linac which implies beam halo collimation in designated areas.

Front End of the Driver Linac

The front end of the RIA driver linac is shown schematically in Fig. 2. It consists of two ECR ion sources, a low energy beam transport (LEBT), a multi-harmonic buncher, a 57.5 MHz RFQ, and, finally, a medium energy beam transport (MEBT) which matches beam into the superconducting linac.

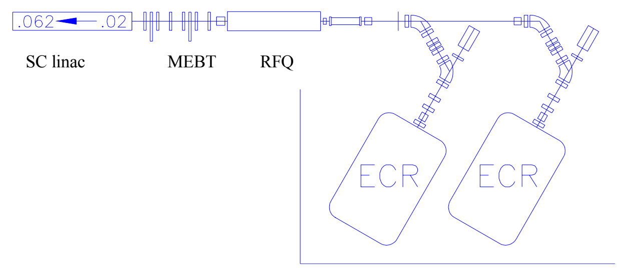

Figure 2: Front End of the RIA driver linac.

An ECR type of source is well matched to the requirement for cw, high-charge-state ion beams over the full mass range. The heaviest beam needed for the RIA driver is uranium, which is the most demanding in terms of ion source performance. The LEBT is designed to select and separate the required ion species and to bunch and match either one or two charge states of ions with masses above 180 into the following RFQ structure [8].

The primary design goal for the RFQ is to establish a low output emittance so that the acceleration of multiple-charge-state beams through the rest of the linac becomes straightforward. As was discussed in our previous work [3], a multi-harmonic buncher must be used upstream of the RFQ to produce the lowest possible longitudinal emittance of two-charge-state beams. The acceleration starts with a small separatrix whose length is kept constant along the RFQ. For the parameters of the RFQ given in ref. [9] the longitudinal emittance at the level 99.9% is less than 2 π·keV/u-nsec for the two-charge-state uranium beam.

Accelerating-Focusing Lattice of the SC linac

The baseline design of the driver linac was described in ref. [10]. Below we present the results of beam dynamics studies for the latest version of the driver linac design which includes the following main modifications: 1) peak surface electric field in all drift-tube SC resonators is assumed to be 20 MV/m except the first seven 4-gap quarter wave resonators; 2) the high-β section of the driver linac contains two types of triple-spoke resonators [5] instead of three types of elliptical resonators operating at a peak electric field 27.5 MV/m.

The linac comprises 352 SC cavities distributed in 68 cryostat modules. Except for the first cryostat which contains seven 4-gap resonators and one 2-gap resonator, the linac consists of 6 different types of cryostats filled by five different types of resonators. Fundamental frequency is 57.5 MHz and the linac comprises SC resonators operating at the 1st, 2nd, 3rd and 6th harmonics. Transverse focussing is provided by SC solenoids contained in the same cryostat modules as the cavities. Such an array, with the cavities operated at a synchronous phase φ_S=-30°, provides strong focussing in both transverse and longitudinal phase space. Due to the strong damping of the bunch phase width as beam energy is increased, some sections of the linac can be set at a synchronous phase φ_S =-25°.

Beam Dynamics Simulations

Beam dynamics studies have been performed with the goal of optimizing the linac structure in order to reduce possible effective emittance growth of the multi-q uranium beam. The end-to-end simulation of beam dynamics is being performed by the TRACK code [11] which integrates the particle equations of motion through the electric and magnetic fields of the SC cavities, the 3D field components having been obtained from numerical solution of Maxwell's equations for each specified cavity geometry. The motion of the particles is traced in 6D phase space, and generally represents the dynamics of the multi-component heavy-ion beams with good spatial resolution. After recent modifications the TRACK code supports all elements of the driver linac such as RFQ, multi-harmonic buncher, bending magnets, magnetic and electrostatic focusing devices. All TRACK elements are represented with realistic three-dimensional field distributions which naturally include fringe fields.

Prior to numerical ray-tracing of mutli-q beam through the linac, the rms transverse and longitudinal beam parameters were matched carefully using fitting codes for a trial beam. A particularly critical aspect of fitting was to avoid beam mismatch at the transitions between focusing periods of differing length and between the cryostats. Note that the focusing lattice length is different for each of the four types of SC cavities. Final adjustment of the longitudinal matching is done by setting appropriate value of synchronous phase. The first-order design of the linac is done by the TRACE-3D code. Beam transport codes such as TRANSPORT, GIOS and COSY were used for the design of multi-q beam transitions and switchyard [3,7,8]. Comparative beam dynamics studies in the high-β section of the RIA driver linac have been performed for two types of accelerating structures: elliptical cavities as in the baseline proposal and triple-spoke cavities.

The simulation starts from the exit of the ECR HV platform. The multi-component heavy-ion beam is transported through the achromatic charge-selection system and accelerated by the RFQ (see Fig. 2). In these simulations, 10^6 particles remaining after the RFQ represent a two-charge state uranium beam in the low-β section, five charge states in the medium-β and four charge states in the high-β section. The envelope of a beam containing 10^6 particles along the SC section of the linac is shown in Fig. 3. The beam is axially-symmetric along the linac but not in the post-stripper MTS. The passage through the strippers was simulated by the SRIM code [12] and the calculated particle distribution was incorporated into TRACK.

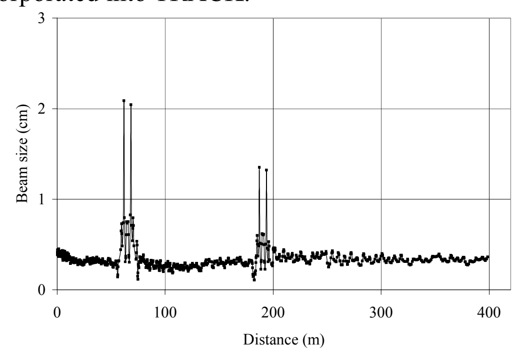

Figure 3: Maximum size of the beam presented by 10^6 particles in the horizontal plane along the driver linac.

For the safety margin, in simulations we have assumed that the standard deviation of the energy straggling is 5 times larger than the value predicted by the SRIM code. This large safety factor is appropriate due to the lack of trustable experimental data for the stripping energy ~85 MeV/u of uranium ions. Table 1 shows the rms and total normalized emittance growth in the driver linac.

Table 1. Rms and total (100% of particles) emittance growth factor in the driver linac.

No errors			
	Horizontal	Vertical	Longitudinal
Rms	1.5	1.5	4.9
Total	4.8	4.9	35
With errors			
Rms	1.8	1.9	9.5
Total	5.8	6.8	35

All errors are randomly generated as a uniform distribution with the rms values given in ref. [9]. The sensitivity of multi-q beam parameters to various types of random errors and misalignments were studied by the ray-tracing code TRACK. The most important errors affecting transverse beam motion are the misalignments of the transverse focusing elements. Due to the strong defocusing of low velocity particles by the SC cavities the misalignments of the SC cavities were also taken into account. Phase and amplitude errors of the rf field are fast fluctuations and produce effective longitudinal emittance growth of multi-q beams. Monte Carlo simulations of the dynamics of multi-q beams in the presence of both accelerating field and alignment errors have been performed. We introduced alignment errors by displacing separately both ends of each solenoid and SC cavity in both X and Y directions. Then we tracked the multi-q beam represented by 10^4 particles through the whole linac and noted the increase in emittance resulting from all types of errors. As was discussed in ref. [4] a multi-q beam requires frequent corrective steering in order to avoid appreciable emittance growth. Therefore, our simulation was done in the presence of steering elements along the linac. This entire simulation was then repeated two hundred times, each time with a different, random set of errors. These studies show that in the worse case both transverse and longitudinal total emittances are well within the linac acceptance. No particle losses along the linac were observed.

Phase space plots obtained during 200 seeds are accumulated and shown in Fig. 4. As is seen the multi-q uranium beam can be accelerated up to 400 MeV/u within ±0.25% energy spread and remains within ±40 psec time width. A longitudinal emittance of 80 π·keV/u-nsec contains all particles shown in Fig. 4.

Recently independent beam dynamics studies of the driver linac for the RIA have been performed at MSU (see, for example, [13]). These studies confirmed all basic concepts for the design of high-intensity SC linacs with the capability to accelerate multi-q beams originally discussed in ref. [1-11].

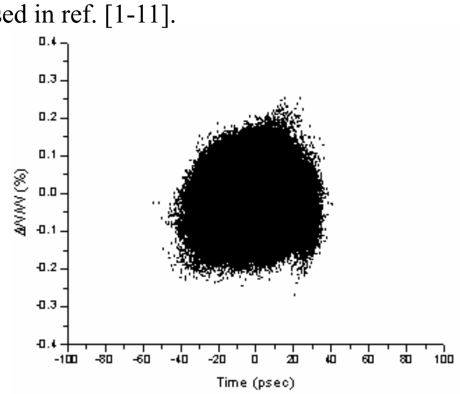

Figure 4: Phase space plots of a four charge state uranium beam at the exit of the driver linac.

POST-ACCELERATORS

The ability to accelerate multi-q radioactive beams (RIB) is especially valuable due to the extremely low intensities of secondary particles. In addition, the intensity of the RIB drops after the strippers which are necessary to reduce the total accelerating voltage. The post-stripper section of the RIA post-accelerator will be designed for the acceleration of multi-q beams to enhance the available beam intensities for experiments. As it was shown in [1] a wide range of the charge spread $\Delta q/q$, about 20%, can be accepted and accelerated in the ATLAS accelerator. In the design of the RIA post-accelerator we have restricted the possible range of $\Delta q/q$ to ≤11% in order to avoid a phase space emittance halo. As a consequence of multi-q acceleration the total acceleration efficiency is significantly higher than for single charge-state beams, as shown in Fig. 5. The RIB linac of the RIA Facility [14] will produce beam intensities higher by a factor of ~20 as compared with post-accelerators based on an ECR charge breeder. As it follows from beam measurements in ATLAS, the transverse and longitudinal emittances of multi-q beams will be larger by a factor of ~3 for the charge spread $\Delta q/q$=20% [1]. The RIA post-accelerator based on ATLAS will provide better beam quality because the charge spread will be restricted to $\Delta q/q$ <11%.

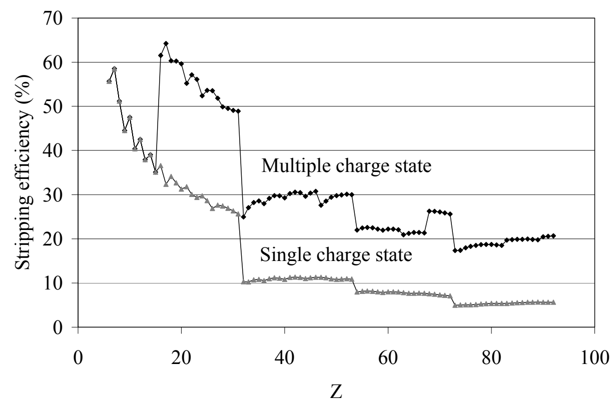

Figure 5: RIB linac overall stripping efficiency in the regime of single and multi-q beam acceleration.

The first RIB linac purposely designed for the multi-q heavy-ion beam acceleration will be commissioned soon at TRIUMF [15]. The project ISAC-II is well advanced and the first stage of the post-accelerator consisting of ~ 20 MV of accelerating voltage is planned for commissioning by April 2005.

The EUROSOL project has been discussed during last several years extensively (see, for example, [16]). The project calls for a 100 MeV/u post-accelerator with multi-q acceleration feature. The latter significantly reduces the required total voltage for acceleration of the heaviest ^{132}Sn ions and provides almost complete transmission after two stripping stages.

Multi-q beam acceptance from charge-breeder

There are wide discussions and proposals to use ECR charge-breeders to produce higher charge state RIBs at very low velocities before the injection into the RFQ or other resonant accelerating structures. For example, this configuration is accepted as a baseline design for the ISAC-II [15] and EUROSOL [16]. A technique to accept two charge states of stable ions from the ECR and accelerate them simultaneously in an RFQ has been reported in ref. [3]. Similar technique can be applied to accept two or three charge states from the charge-breeder of radioactive ions. Figure 6 shows an injector configuration which can accept three charge states from the charge-breeder and accelerate them in the RFQ. In this particular example the RFQ has similar parameters as the ISAC-I RFQ operating at 35 MHz and accelerating ions with minimum charge-to-mass ratio 1/30 from 2 keV/u to 150 keV/u [17]. Two bending magnets 2 and two electrostatic quadrupoles 3 are tuned to provide an achromatic bend of three charge states. The multi-

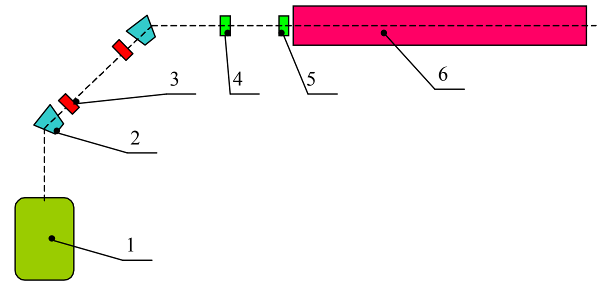

Figure 6: Schematic layout of the multi-q RIB injector. Legend: 1 – charge breeder; 2 – 45° bending magnet; 3 – electrostatic quadrupole; 4 – multi-harmonic buncher; 5 – resonator, 6 – 35 MHz RFQ.

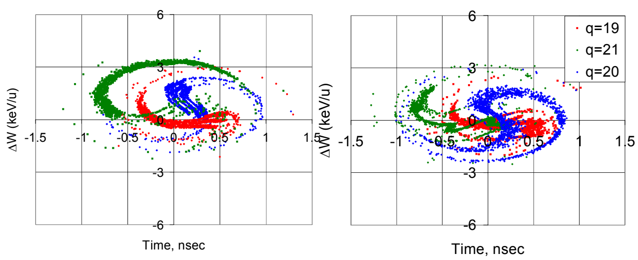

Figure 7: Phase space plots of three-charge-state gold beam at the exit of the RFQ.

harmonic buncher (MHB) 4 operating at fundamental frequency 35/3 MHz modulates ion velocities of three neighbouring charge states. Over the drift space from the MHB 4 and following resonator 5 the distance between the bunches of charge states q-1, q and q+1 becomes equal to 120° at the fundamental frequency. Therefore in the RFQ, each charge state occupies its own bucket. The resonator 5, operating at the fundamental frequency, serves as a velocity equalizer (VE). It does not change the velocity of the ion with central charge state q but equalizes velocities of ions with charge states q-1 and q+1. The straight section of the LEBT upstream of the RFQ is filled by the focusing elements which provide matching to the RFQ acceptance.

As an example, we have designed the injector and simulated a ^{200}Au ion beam with charge states 19,20,21 from the ECR source to the end of the RFQ. If beam matching is done carefully there is no transverse emittance growth of a three-charge-state beam.

Acceleration of a three-charge-state beam can be done with and without the VE. Using the VE one can get lower longitudinal emittance of multi-q beam. However the energy acceptance of the RFQ is large and three- charge-state beams can be accelerated without any VE with the same efficiency 89% as for the single-charge-state beam. Table 2 shows the longitudinal rms emittance for three regimes of the injector operation: acceleration of a single charge state and 3 charge state acceleration with and without the VE. Figure 7 shows phase space plots for a three-charge-state beam without the VE (the left plots) and with the VE (the right plots). As is clear the velocity equalizer helps to produce brighter beam in the longitudinal phase space and reduces rms emittance of the accelerated multi-q beam.

Table 2. Longitudinal rms emittance at the exit of the RFQ (π·keV/u-nsec)

Single q	3-q with VE	3-q without VE
0.16	0.35	0.63

CONCLUSION

The capabilities of SC linacs to accelerate intense heavy-ion beams can be substantially improved by the multiple-charge-state beam acceleration. These results have important implications for the proposed RIA facility for short-lived beams of nuclei. The technique is widely accepted by accelerator physicists worldwide and a number of heavy-ion linacs are being designed with multi-q beam accelerating capability.

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