Simultaneous Acceleration of Multiply Charged Ions through a Superconducting Linac

P. N. Ostroumov, R. C. Pardo, G. P. Zinkann, K. W. Shepard, and J. A. Nolen
Physics Division, Argonne National Laboratory, 9700 S. Cass Avenue, Argonne, Illinois 60439

(Received 8 November 2000)

The possibility of simultaneously accelerating particles with a range of charge-to-mass ratios (~20%) to the same energy is proposed and demonstrated for a superconducting linac. Uranium ions stripped in a foil with eight charge states have been accelerated through a portion of the ATLAS linac from 286 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. This development has immediate application to the high-intensity acceleration of heavy ions that are limited by ion-source intensities, such as the proposed Rare Isotope Accelerator Facility.

DOI: 10.1103/PhysRevLett.86.2798 PACS numbers: 29.17.+w, 29.27.Bd

Particle accelerators are generally used to accelerate one species of particle at a time (electrons, protons, or heavier ions) to a given energy. This is intrinsic to circular accelerators that combine electric and magnetic fields and therefore are restricted to the acceleration of a single value of the charge-to-mass ratio. Similarly, room temperature rf linacs, in principle, have the capability for accelerating a range of charges to the same final velocity by adjusting accelerating field level in proportion to the charge-to-mass ratio. Superconducting (SC) rf linacs, with individual resonant cavities whose relative phases and accelerating field levels are completely independent of each other, are suitable for acceleration of lighter ions to higher energies per unit mass. Such capability is especially useful in medium energy (several hundreds of MeV/u) linacs for the production of various ion beams, from protons to uranium.

The possibility that a linear accelerator could accelerate particles with different charges simultaneously has been known for some time. Notably, proton linacs have accelerated both positive and negative hydrogen ions using the change in the sign of the rf accelerating field when 180° out of phase [1]. With superconducting linacs, where the phase of each cavity is controlled separately, this concept can be generalized to accelerate a range of charge states with the same mass, provided the phases of the bunches can be controlled precisely. This concept 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 accelerating fields. Such linacs are being considered for major facilities for nuclear physics research [2]. For example, accelerating on the order of a few times 10^{13} uranium nuclei per second 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. A scheme where essentially all the charge states can be accelerated saves ~80% of the beam thus providing up to 2 orders of magnitude more beam at the desired final energy.

The simultaneous acceleration of neighboring charge states becomes possible because the high charge-to-mass ratio makes the required phase offsets small. We note that different charge states (q_i) of equal mass will have the same synchronous velocity profile along the linac as a reference charge state (q_0) if the condition

$$\left(\frac{q}{A}\right)_i \times \cos\phi_{s,q_i} = \left(\frac{q}{A}\right)_0 \times \cos\phi_{s,q_0} \qquad (1)$$

is fulfilled. The simultaneous acceleration of ions with different charge states requires an injection of the beam with each charge state q at a synchronous phase determined from Eq. (1):

$$\phi_{s,q_i} = -\arccos\left[\frac{q_0}{q_i} \times \cos\phi_{s,q_0}\right]. \qquad (2)$$

Figure 1 shows the synchronous phase as a function of uranium charge state when the linac is tuned for q_0 and its synchronous phase is $\phi_{s,q_0} = -30°$. As is seen in this figure some charge states below and above q_0 can be accepted and accelerated.

Bunches with different charge states can be injected into the linac at slightly different rf phases in order for each charge state to be matched precisely to its own phase trajectory. The higher the charge state, the sooner it must arrive at the SC cavity to be matched. One possible method

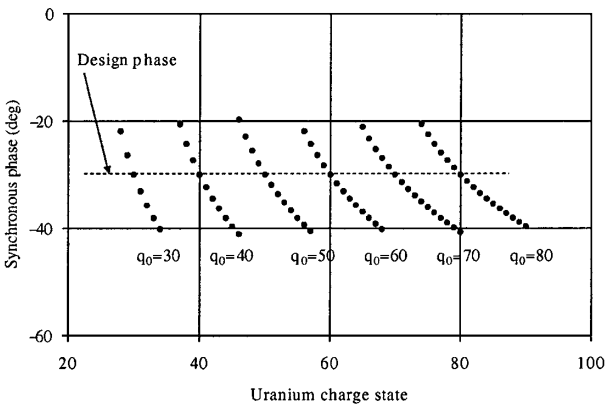

FIG. 1. Synchronous phase as a function of charge state. The groups of points indicate the phases for charge states around mean values of q_0.

for adjusting the phase of multiple charge states would be a suitable magnetic system combined with rf cavities.

Even if the bunch centers of each charge state are matched to their own synchronous phase the total effective emittance of the simultaneously accelerated multiple charge-state beam depends on the accepted spread of charge states Δq and will be larger than the emittance of the individual beams.

The spread in charge states that can be accepted for acceleration [3] depends primarily on the extent that the focusing system can limit emittance growth in transverse phase space. Consequently, 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, about $\pm 10\%$, can be accepted and accelerated. However, in high intensity ($\sim 10^{13}$ uranium nuclei per second) and medium energy (~ 400 MeV/u) the tolerable spread of charge states is significantly lower.

Standard periodic focusing theory can be used to analyze the simultaneous acceleration of the several charge states. For example, a spread in charge states of $\pm 2.6\%$ produces a total transverse emittance growth of 6%. This is caused by slightly mismatched conditions for different charge states in the periodic focusing channel with a 60° phase advance per period [3]. There is an additional effect, because in practice, focusing elements are aligned with some residual errors, which results in a tilt of the magnetic axis of the focusing elements with respect to the common accelerator axis. The different charge states have different betatron periods (rate of rotation in transverse phase space). As the beam proceeds along the linac, the transverse coherent oscillations of the various charge states eventually become uncorrelated and the effective total emittance, summed over all charge states, increases. This effect restricts the tolerable charge spread in the linac. Our simulations [2] show that an alignment error of the SC solenoids of ± 300 μm limits the tolerable charge spread to the value $\pm 3\%$ if simple corrective procedures are applied.

For most applications, relatively few charge states need to be accelerated simultaneously. Therefore, as is seen from Fig. 1, the differences in the matched synchronous phases are just a few degrees; a 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.

A test of this concept with uranium beams was performed at the 50 MV SC linear accelerator at Argonne National Laboratory (the ATLAS accelerator). A simplified layout of the linac is shown in Fig. 2. The unintentional acceleration of several charge states of uranium has been observed at the ATLAS booster in the "normal" configuration. However, the unwanted charge states were considered parasitic. Therefore systematic studies of all the accelerated charge states had not been previously performed.

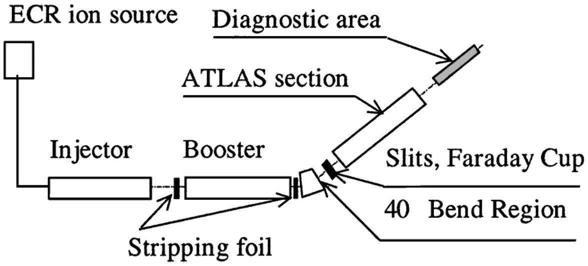

FIG. 2. Simplified layout of the ATLAS linac.

The beam dynamics in the booster were simulated with the modified LANA code [4]. At the position of the stripping foil, input beam parameters were assumed to be the same for all charge states. The longitudinal and transverse normalized emittances were taken to be $\epsilon_L = 2\pi \times \mathrm{keV}/u \times \mathrm{nsec}$ and $\epsilon_T = 0.25\pi \times \mathrm{mm} \times \mathrm{mrad}$. The ray-tracing code incorporated the actual resonator field profiles and the field levels of the superconducting cavities. The synchronous phase for $^{238}\mathrm{U}^{+38}$ was set to $-30°$. Figure 3 shows the calculated longitudinal phase space at the booster exit. As is seen, one can expect that most of the charge states produced in the stripper foil can be accelerated.

The $^{238}\mathrm{U}^{+26}$ beam from the ATLAS electron cyclotron resonance ion source was accelerated to 286 MeV (~ 1.2 MeV/u) in the injector linac (see Fig. 2) and stripped in a 75 μg/cm^2 carbon foil 0.5 m before the booster linac as shown in Fig. 2. The mean charge state was 38^+. The beam energy was measured by a resonant time-of-flight (TOF) system [5].

As in the standard operation of ATLAS, the synchronous phase in all 24 cavities of the booster was set by an

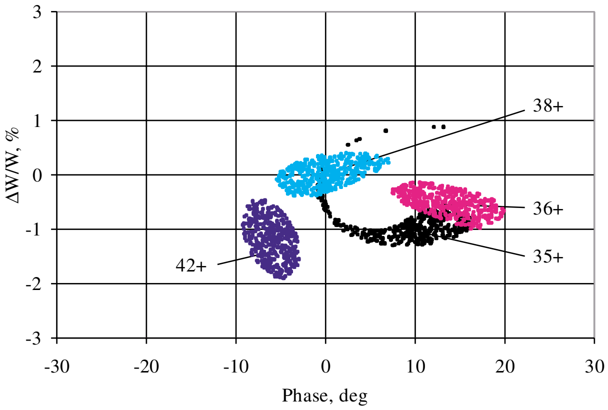

FIG. 3 (color). Longitudinal phase space plots of the accelerated multiple charge-state uranium beam exiting the booster. (For clarity the charge states 37+, 39+, 40+, and 41+ are not shown.)

autoscan procedure using a silicon detector for energy measurements with a ^{58}Ni^{+9} guide beam. A guide beam with a similar charge-to-mass ratio and an identical velocity and arrival time at the entrance to the booster linac was used in tuning the booster so that there was no ambiguity in determining the proper resonator phase settings to obtain the desired synchronous phase angle for ^{238}U^{+38}. Tuning of the focusing fields to get 100% transmission was also accomplished with the guide beam prior to switching to the uranium beam.

The stripped uranium beam was injected into the booster. For initial tuning the slits in the 40° bend region were used to cleanly select only the charge state 38^+. An empirical tuning based on maximum transmission through the system was applied to injected uranium beam parameters as well as to the booster phase setting. After this tuning the total transmission for all charge states measured after the booster was 94%. Figure 4 presents the intensity distribution of the mixture of multiple charge-state uranium beams accelerated in the booster. The difference from the expected Gaussian distribution is caused mainly by poorer transmission of lower charge states through the booster.

The individual charge states then were analyzed in the 40° bend region and sent to the ATLAS beam diagnostics area (see Fig. 2). The parameters measured for each charge state were (a) transverse emittance (the value and ellipse orientation in phase space) by the help of quadrupole triplet gradient variation [6] and a wire scanner located 3.1 m apart, (b) the average energy of the beam using the ATLAS TOF energy measurement system, and (c) the energy spread, with the silicon detector measuring the time width of the bunches after a drift space to the ATLAS diagnostics area.

The multicharged uranium beam was stripped for the second time at the exit of the booster and ^{238}U^{+51} was selected, because the present beam transport system does not allow for multiple charge states. The same beam parameter measurements were performed and the beam was further accelerated in the last section of ATLAS. The use of a multicharged uranium beam increased the final intensity of the doubly stripped ^{238}U^{+51} beam by 4 times with respect to what would have been obtained in normal operation conditions. This beam was accelerated up to 1400 MeV and used for a scheduled experiment at ATLAS.

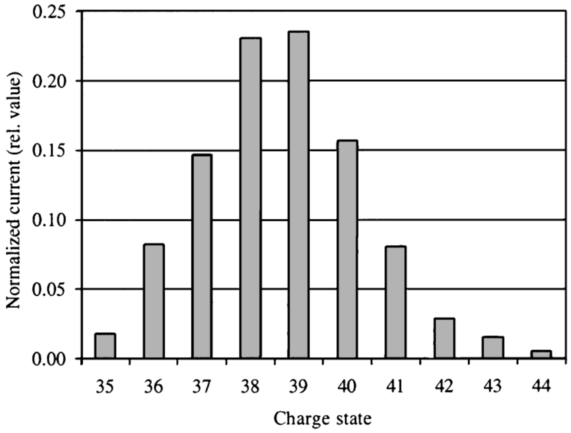

FIG. 4. Intensity distributions for accelerated multiple charge uranium beams.

The results of individual transverse emittance measurements are presented in Table I. Only vertical emittances are shown, because the horizontal emittance was limited by slits after the bending magnets. The doubly stripped uranium beam ^{238}U^{+51} contains all the information about the effective emittance of multiply charged beams from the booster, since all the charge-state components from the booster contributed to it.

As may be seen in Table I the beam phase space ellipse parameters, or Twiss parameters, differ only slightly for various charge states and doubly stripped uranium beam. These differences in the Twiss parameters are responsible for the effective emittance growth which was a factor of 2 in our experiment.

The average energy and the FWHM energy spread of individual charge states are shown in Fig. 5. For the simulation of energy spread, the input longitudinal emittance $\epsilon_L = 2\pi \times \mathrm{keV}/u \times \mathrm{nsec}$ was assumed. The graphs show a consistent behavior of the energy spread as a function of charge state. There is some discrepancy in the average energy for the extreme charge state, probably caused by a combination of longitudinal tuning errors in phases and amplitudes of the 24 SC cavities and due to the difficulty in precisely matching the energy and initial phase of the guide beam to the uranium beam. Such tuning in high intensity machines can be done with better precision. Even with these tuning errors, the average energy spread for three neighboring charge states 37, 38, and 39 is only 0.7%. The measured energy spread for a single charge state (38^+) was 0.4% FWHM. The measurement was repeated after the beam went through the second stripper foil so that the different components were distributed among a new set of equilibrated charge state, and the measured value was 1.3% FWHM.

The capabilities of SC linacs to accelerate intense heavy ion beams can be substantially improved by this technique.

TABLE I. Twiss parameters of single charge-state beams at the exit of ATLAS for the vertical plane.

Uranium charge state	α_Y	β_Y mm/mrad	$\epsilon_{Y,\mathrm{normalized}}$ $\pi \times$ mm $\times$ mrad
36+	0.72	12.66	0.94
37+	0.48	8.08	1.24
38+	0.06	10.17	1.11
39+	0.45	7.60	1.34
40+	0.54	9.22	1.03
41+	−0.18	9.20	0.89
51+	0.60	9.00	2.69

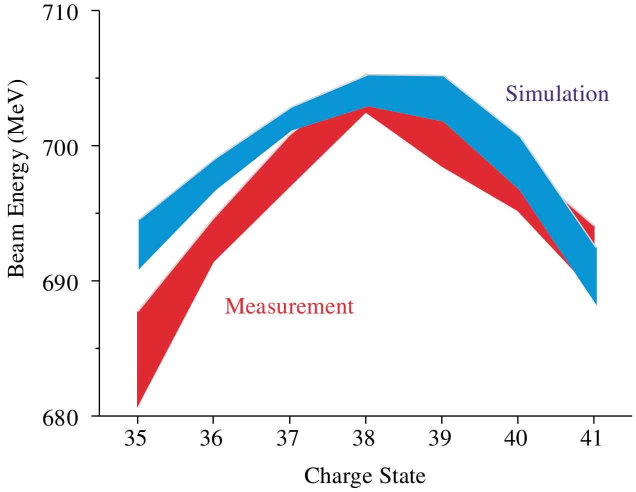

FIG. 5 (color). Beam energies of individual charge states. Vertical width corresponds to the FWHM energy spread.

The result has important implications at present for the proposed facility for short-lived beams of nuclei (Rare Isotope Accelerator Facility), where intense beams of ions will be accelerated to 400 MeV/u. For beams such as uranium, where the demonstrated capability of ion sources is limited, and where multiple stripping had been envisioned, the development will increase the particle intensities by more than an order of magnitude.

This work was supported by the U.S. Department of Energy under Contract No. W-31-109-ENG-38.

[1] D. E. Nagle, in *Proceedings of the 1972 Proton Linear Accelerator Conference, Los Alamos, 1972,* edited by K. H. Harper (U.S. Atomic Energy Commission, Oak Ridge, TN, 1972), p. 4.
[2] K. W. Shepard *et al.,* in Proceedings of the 9th International Workshop on RF Superconductivity, Santa Fe, New Mexico, 1999 (to be published).
[3] P. N. Ostroumov and K. W. Shepard, Phys. Rev. ST Accel. Beams **3**, 030101 (2000).
[4] D. V. Gorelov and P. N. Ostroumov, in *Proceedings of the Fifth European Particle Accelerator Conference, Sitges, Spain, 1996,* edited by R. Pascual (Universitat Autonoma de Barcelona, Barcelona, Spain, 1996), p. 1271.
[5] R. Pardo *et al.,* Nucl. Instrum. Methods Phys. Res., Sect. A **270**, 226 (1988).
[6] P. N. Ostroumov *et al.,* in *Proceedings of the Third European Particle Accelerator Conference, Berlin, 1992,* edited by H. Henke, H. Homeyer, and Ch. Petit-Jean-Genaz (France Editions Frontiers, Gif-sur-Yvette, 1992), p. 1109.