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CONCEPT FOR SIMULTANEOUS ACCELERATION / DECELERATION OF HEAVY IONS IN
A SINGLE RF LINAC*

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ABSTRACT

This paper outlines a concept for obtaining highly-stripped low-velocity heavy ions by accelerating an ion beam with an rf linac and then, after stripping, using the same linac to reversibly decelerate the beam back to the injection energy. The synchronous-phase requirement and the matching relationship in longitudinal phase space are stated, and a realistic example of these relationships is given for a ^{58}Ni beam. The probable performance characteristics of the ATLAS superconducting linac operated in this new accel/decel mode are discussed.

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1. INTRODUCTION

Recently there has been considerable interest in obtaining highly-stripped low-velocity ions by first accelerating, then stripping, and finally decelerating the stripped ions to some low energy. Several schemes for implementing this idea have been demonstrated [1-5] and others have been discussed, but they all suffer from the drawback that two major accelerator components are required: an accelerator and a separate decelerator. The purpose of this note is to outline an alternative approach in which a single linear accelerator is used for both acceleration and deceleration.

It is common knowledge that an rf linac cannot be used for multiple-pass acceleration of non-relativistic ions because the beam can not be matched to the velocity profile of the linac for more than one pass. This statement is true whether the velocity profile is determined by the spacings of a multiple-gap accelerating structure or by the phasing of short independently-phased structures. It seems worth while to point out, however, that a single linac can in principle be used to accelerate an ion beam and then decelerate the same beam after it has been stripped to a higher (or lower) charge state. A preliminary examination suggests that this approach is a practical and cost-effective way in which to produce highly-charged low-velocity ions.

2. GENERAL Features of the Concept

The main functions of the proposed accel-decel scheme are shown in fig. 1. The beam from the ion source is bunched, injected into the linac with energy U_1 and charge state q_1 , accelerated by the linac to energy U_2 , stripped to charge state q_2 , turned around, and reinjected into the high-energy end of the linac. We assume that space-charge effects can be neglected. Then, if

the linac is accurately straight and if the transverse and longitudinal phase space of the reinjected beam are properly matched to the linac, one has (to at least first order) a reversible process in which the beam is decelerated with the same velocity profile as was present for acceleration. Thus, the central ray (in space and time) of the ion beam will emerge at the source end of the linac with charge state q_2 and with the same energy U_1 as at injection. The questions addressed by this paper are whether imperfect matching of the reinjected beam, energy and angular straggling in the high-energy stripper, and the change in the charge state destroy this reversibility enough to cause the quality of the decelerated beam to deteriorate badly.

In order to have the same velocity profile for the forward- and backward-moving beams, the synchronous phases ϕ_s of the two beams should satisfy the relationship

$$q_1 \cos \phi_{s1} = - q_2 \cos \phi_{s2}, \quad (1)$$

where the phase convention is defined by the statement that the accelerating field is $E_a \cos (\omega t - \phi_s)$. If eq. (1) is satisfied for the central ray of the beam, then one has considerable latitude as to the shape of the reinjected longitudinal phase ellipse, but a matched ellipse for the new charge state is optimum. For the idealized case of a linac with continuous acceleration, the matching condition [6] is

$$\Delta V = 115 \left[\frac{q}{A} E_a f \sin (-\phi_s) \right]^{1/4} A^{1/8} E^{3/8} (\Delta E \Delta t)^{1/2}, \quad (2)$$

where the energy spread ΔU is in MeV, the accelerating field E_a is in MV/m, the rf frequency f is in Hz, and the time spread Δt is in seconds.

From eq. (2) we see that $\Delta E \propto [q \sin(-\phi_s)]^{1/4}$, which is not a very sensitive dependence on q .

Consider a typical beam such as ^{58}Ni with $q_1 = 15$ and $\phi_{s1} = 15^\circ$. Then, $\phi_{s2} = 61.1^\circ$ and the energy spread before and after the high-energy stripping should satisfy the ratio $\Delta U_2/\Delta U_1 = 1.61$. This example is illustrated in fig. 2, where the acceptances of the two beams are plotted (see Ref. 7 for a general discussion of the region of stability.) One sees that the change in charge state causes the longitudinal acceptance of the linac to be greatly enlarged, and the change in the shape of the matched phase ellipse causes no problems. Indeed, the linac could obviously accept a very badly matched beam. Also, a reasonable error in the phasing of the reinjected beam is unimportant because it merely causes the central ray of the phase ellipse to rotate around the synchronous phase during deceleration. Note that all of this behavior of the beam during deceleration is conceptually identical to the behavior during the simultaneous acceleration of several beams with different charge-to-mass ratio.

Similar and obvious considerations show that the reinjected beam can be matched in transverse phase space if the focusing provided by the lenses within the linac is strong enough to counterbalance the combined effects of the beam emittance and the defocusing caused by the accelerating structures. Since defocusing by the accelerating structures varies as $q \sin \phi_s$, it increases rapidly with increasing q and the reinjected beam might blow up in some linacs. However, this is not a problem for ATLAS (the linac of interest to us) because its focusing solenoids are closely spaced and have very short focal lengths, the focusing power of the solenoid varies as q^2 , and the acceptance of the linac for the accelerating beam is very much greater than it needs to be. The main problem with transverse phase space is likely

to be associated with alignment problems that induce or require steering along the accelerator system, since a magnetic field bends the outgoing and returning beams in opposite directions.

Some of the quantitative aspects of the above discussion are based on the assumption that the linac provides continuous acceleration, an assumption that is not accurate for the ATLAS superconducting linac, which consists of short (3-gap) independently-phased resonators. Nevertheless, for such a linac eq. (1) is still valid, and eq. (2) and fig. (2) are qualitatively correct if the accelerating field E_a is interpreted as being the average field within the whole linac. In any case, the concept that the central ray of the reinjected beam can retrace its accelerating velocity profile is valid, whatever the exact matching condition may be.

Perhaps the primary question about the reinjected beam is its transmission at the low-velocity end of the machine. Clearly, there is some emittance grow (in both longitudinal and transverse phase space) during acceleration. This growth will continue during deceleration since the phase ellipses rotate in the same direction as during acceleration (see fig. 2). The enlargement in the longitudinal phase space during deceleration is expected to be small because the high charge state of the returning beam forces operation in a very linear part of the accelerating-field wave form. No simple statement can be made about emittance growth in transverse phase space because it depends on the configuration and strength of the focusing elements. However, for many linacs the emittance growth is expected to be roughly the same as for an equivalent accel-decel system consisting of two independent linacs.

The impact of energy and angular straggling in the high-energy stripping foil can be made small by arranging to have the stripping take place

at waists in both longitudinal and transverse phase space. Also, any energy loss in the stripping foil can be replaced by adjusting the phase of the rebuncher in the turn-around region.

3. POSSIBLE Application at ATLAS

The prototype "booster" linac [8] of the ATLAS system is particularly attractive for the accel-decel concept discussed here because the acceptance of the linac is so very much greater (in both longitudinal and transverse phase space) than is normally required. This desirable characteristic results from many design features: the low rf frequency of the resonators, the large apertures of their drift tubes, a large number of focusing lenses (superconducting solenoids), the strong focusing power of these lenses, the close packing of the active elements, and the good quality of the incident beam. As a result, the booster linac easily transmits 100% of the beam even when the incident beam is poorly matched, and it seems likely that 100% of the decelerated beam can also be transmitted. In this connection, note that the booster has an appropriate velocity profile for a backward moving beam, unlike the situation in the deceleration tests that have been carried out previously with this and other linacs.

The positive-ion injector [9-11] that is planned as a replacement of the present tandem injector in the ATLAS system may offer an exceptional opportunity to implement the ideas outlined in this paper. For this all-linac accelerator, intense beams of highly-stripped ions will originate in an electron cyclotron resonance source, be injected into a new class of superconducting injector linac that will provide ~ 12 MV of acceleration, and then proceed along a straight line into the existing booster linac that provides an additional ~ 20 MV of acceleration. The main technical

uncertainty about the use of this system for accel-decel is whether the acceptance of the injector linac is large enough to transmit all of the returning beam. Although the transverse acceptance of the low-energy end of the injector is considerably smaller than that of the booster linac, the emittance would have to grow by more than a factor of 4 before much beam is lost. Thus, it is probable that transmission of the returning beam is not a serious problem, but this question has not yet been studied quantitatively. In any case, because of the high intensity of the beams available from the ECR source, a large loss could be tolerated for many uses.

The 15-m space between the injector and booster linacs allows one, in principle, to have considerable flexibility in the operation of the system for accel-decel. For example, by separating the outgoing and returning beams in this region, the maximum energy U_2 can be increased by stripping the outgoing beam without changing the charge of the returning beam. Also, the returning beam can be steered in order to correct for alignment errors; and the phase can be adjusted so as to cause the central ray of the returning beam to rotate around its synchronous phase, thus providing a way to obtain some variation in the energy of the extracted beam.

Since the ATLAS injector-booster linac system will already exist, the main cost in the use of the system for the accel-decel mode outlined here would be for beam turning and beam matching at the high-energy end. These functions involve non-trivial design problems that are well beyond the scope of this paper.

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Figure Captions

- Fig. 1 Schematic representation of the main functions in a reversible acceleration - deceleration linac system for heavy ions.
- Fig. 2 Longitudinal phase space available for acceleration and deceleration of 500-MeV ^{58}Ni ions for which $q_1 = 15$, $q_2 = 28$, $\phi_{s1} = -15^\circ$, and $\phi_{s2} = -(180^\circ - 61.1^\circ)$. The black dots at the two synchronous phases ϕ_{s1} and ϕ_{s2} represent the phase ellipses for outgoing and returning beams in the high-energy end of the ATLAS booster linac [8].

Fig. 1