LBL-18970

TWO-DIMENSIONAL LINACS*

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We describe several schemes for rf acceleration of ribbon beams. (Although the ribbon edges of course, need to be focussed, these configurations are essentially 2-D.) They allow simpler modeling than quadrupole systems and, if operable, provide good matching to certain types of ion sources and beam neutralizers. We discuss four possible configurations, in chronological order of conception: (1) an rf linac with dc transverse field focussing; (2) a similar linac, also with many pairs of electrodes, but using rf focussing; (3) an RFQ-like configuration with continuous electrodes, in which energy changes slowly along the beam axis; and (4) a similar system in which the beam energy oscillates along the axis. We discuss some of the advantages and disadvantages of these systems, and analyze the last case in some detail.

Introduction

For some applications, it is desirable to develop accelerators capable of accelerating relatively large cw beam currents (several amperes) to modest energies of a few MeV. An example is the use of beams of neutral hydrogen atoms for heating or driving circulating currents in tokamak fusion reactors. For such an application, currents of some 10's of amperes of H^- ions would be needed at energies up to 1 MeV. As it is not clear that this goal can be readily achieved with dc accelerators, it is reasonable to search for methods of rf acceleration of such beams.

Sheet beams of ions offer advantages for this particular application.[1] One common type of H^- ion source in use produces a sheet beam, so the need for accelerators and transport systems to handle a beam of this configuration arises naturally. A stripper for removing the electron from the H^- ion and converting it to a fast H atom in a neutral beam system might consist of a gas cell, a plasma cell, or the resonant cavity of a powerful laser. In all three cases, the desire to minimize gas input from the stripper into the system or to minimize power lost to the mirrors, in the case of the laser photoneutralizer, dictates the use of a sheet beam. A further advantage of the sheet beam configuration for this application is the fact that electrostatic systems capable of transporting such a beam are actively under investigation;[2] these systems could be used, for example, to transport the already accelerated sheet beam through a maze in the neutron shielding around a fusion reactor to minimize radiation damage and minimize activation of the source and accelerator by fast fusion neutrons escaping from the reactor. These thoughts lead us to the consideration of accelerating and transport structures capable of handling sheet beams of ions.

We therefore restrict our discussion in this paper to two-dimensional systems, which, while relatively easy to analyze, require a means of preventing the beam from leaking out the edges of the structure. A scheme for the required beam edge confinement has been described,[3,4] and is being investigated experimentally.[5] An alternative approach in avoiding edge effects is the development of structures capable of rf acceleration of thin tubular beams.[6]

Classifications

Several possible schemes for rf acceleration of sheet beams come to mind. In the first, sets of curved electrodes with a static transverse electric field between them are used for beam transport and serve as drift regions for the beam; acceleration is provided by rf fields in the gaps between pairs of such electrodes. Beam transport through such a Transverse Field Focussing (TFF) structure is well understood theoretically,[7] and the extension of the theory to rf acceleration should be a straightforward matter, as the existing body of theory for drift-tube linacs can be applied. This type of accelerator is a direct analog of a drift-tube Wideröe linac, but with electrostatic fields providing focussing in the drift regions, and could be used for H^- beams up to a few MeV in energy.

A reasonable extension of this type of accelerator would substitute rf fields for the electrostatic fields in the drift regions, and would yield an all-rf system, without the need for dc power supplies.

We have not investigated the properties of the latter type of sheet-beam linac in any detail.

A second broad class of rf linacs capable of transporting and accelerating sheet beams utilizes suitably shaped continuous electrodes. If the electrodes are curved, so as to more or less follow the undulating trajectory of the particle, the particle energy can change slowly along the beam axis. If the electrodes are straight and parallel, with the addition of "ripples" on the surfaces, the particle energy oscillates along its trajectory. In this case, however, the analysis of single particle trajectories in vacuum fields, without space charge, is fairly simple, and it is this case that we have analyzed.

Analysis of a continuous electrode accelerator

This type of sheet-beam linac is conceptually similar to an RFQ, in that surface modulations on the electrodes are expected to focus and accelerate the particle. The potential between pairs of electrodes with a particular offset wavy surface modulation can be represented by the complex potential

$$V(z,t) = [Az+B\cdot\exp(i\Theta)\cdot\sin(kz)]\cdot\cos(\omega t + \varphi). \quad [1]$$

Here z represents the complex variable x + iy; A, B, and Θ are real constants. The imaginary part of V(z,t) represents the actual spatial potential distribution; the electrode shapes required to generate this distribution can be determined by setting Im V equal to the electrode potential and solving for y(x). An example of such electrodes is shown in

* This work was supported by the U.S. Department of Energy under Contract No. DE-AC03-76SF00098, and by the U.S. Department of Defense, Contract MIPR No. W31RPD-43-Z840.

Fig. 1. The frequency of the rf field is ω, and the rf phase angle is φ. We assume that the electrostatic limit is valid (rf wavelength >> dimensions of structure). The wave number k can be any analytic function of z; a suitable choice of k(z) permits the wavelength of the ripple on the electrodes to vary so that an accelerating particle stays in phase with the rf field.

The complex electric field $E = E_x + iE_y$ can easily be derived from this potential, because its complex conjugate, E^*, is given by[8]

$$E^* = i\,\frac{dV}{dz}\,. \qquad [2]$$

The electric field E(z) can be resolved into three terms, which we will do later in this paper. The terms represent an oscillating transverse field and two waves, one moving in the forward (+x) direction, and the other moving in the backward direction.

It can be shown that the oscillating field due to the A term in Eq. [1] contributes nothing to the stability of the particle motion; in this paper we drop the A term when discussing particle dynamics and reinstate it only when calculating electrode shapes (cf Fig. 1).

The condition that a particle moves in synchronism with the forward wave is

$$\mathrm{Re}(kz) = \omega t. \qquad [3]$$

As we show later, we must set $\theta = \pi/2$ in order to have an equilibrium orbit. When we set A = 0, the equilibrium orbit lies on the x-axis, and Eq. [3] becomes

$$k_x x = \omega t. \qquad [3a]$$

If we also neglect the backward wave term, the equilibrium particle sees a time-independent but space-dependent field

$$E_x = \frac{-B}{2}\,\frac{d(k_x x)}{dx}\,\cos\varphi \qquad [4]$$

The particle can gain energy from this field; the change in energy is

$$\Delta W = -\,\frac{qB}{2}\cos\varphi \cdot k_x x \qquad [5]$$

or from Eq. [3a],

$$\Delta W = -\,\frac{qB}{2}\cos\varphi \cdot \omega t. \qquad [6]$$

We are interested for the proposed application in the acceleration of <u>negative ions</u>, and throughout this paper we take the charge q and the charge-to-mass ratio η to be <u>negative</u>. With this assumption, we see from Eq. [6] that for acceleration, we require $\cos\varphi > 1$, or

$$-\frac{\pi}{2} < \varphi < \frac{\pi}{2}$$

The rate of energy gain must be such that the reference particle stays in step with the increasing ripple wavelength. This requirement leads to a second condition for synchronism with the forward wave:

$$v^2 = v_0^2 - \eta B \cos\varphi\, k_x x \qquad [7]$$

where v is the velocity of the particle and v_0 is its value at t = 0.

The simultaneous solution of Eqs. [3] and [7] by elimination of v gives the required solution $k_x(x)$ from which k(z) can be obtained. Rather than presenting the exact solution, we examine the stability properties of this type of accelerator by using the first-order approximation

$$k(z) = k_0(1+az), \qquad [8]$$

where

$$a = \frac{\eta B k_0}{4v_0^2}\,\cos\varphi \qquad [9]$$

In this paper we assume that φ is fixed. Physically, a is proportional to the ratio of the energy gained in one period to the initial kinetic energy of the particle. The particle gains a fixed amount of energy per period; this type of accelerator is similar in that sense to a Wideröe linac.

We now use this form for k(z) to investigate the stability problem. First we have to calculate the electric field seen by the moving particle.

$$E^*(z) = i\,dV/dz = i[A + B\cdot\exp(i\theta)\cdot d(kz)/dz\cdot \cos(kz)]\,\cos(\omega t + \varphi). \qquad [10]$$

If we now expand this expression, using trigonometric identities to eliminate terms of the form $\cos(\alpha)\cos(\beta)$ and $\sin(\alpha)\sin(\beta)$, and ignore small quantities, we find time-independent imaginary terms, indicating static fields in the y-direction in the frame of the moving particle, of the form (for $x \approx 0$)

$$i(Bk_0/2)\cos(\theta)\cosh(k_0 y)\,\cos(\varphi).$$

To eliminate these fields, which would sweep the particle into an electrode, we require

$$\theta = \pi/2. \qquad [11]$$

Physically, θ is related to the offset of the pattern of ripples in one electrode from that of the other. Making the above choice, we are left with

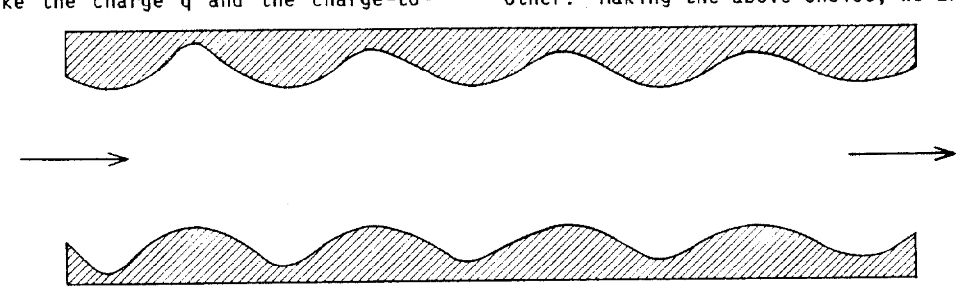

Figure 1. Example of analytic electrode shapes. The initial energy gain per period here is 10%, and the phase angle φ is $\pi/4$. The exact result for k(z) was used rather than the approximation given by Eq. (8).

$$E^* = iA\cos(\omega t+\varphi) - (Bk_0/2)[(1+2ax)+i2ay] \cdot [\cos(\mathrm{Re}(kz)-\omega t-\varphi) + \cos(\mathrm{Re}(kz)+\omega t+\varphi) - ik_0y(1+2ax)(\sin(\mathrm{Re}(kz)-\omega t-\varphi)+\sin(\mathrm{Re}(kz)+\omega t+\varphi))], \quad [12]$$

which represents an oscillating field in the y-direction, perpendicular to the electrodes, and two traveling waves, moving in the + and - x-directions.

The oscillating field A term will be dropped for the reason already given. We assume that the high frequency of the backward wave, as seen by a particle traveling with the forward wave, causes effects that average out, and drop this term also. We are left, then, with fields in the frame of the moving particle that have only dc components.

For an analysis of axial (phase) stability, we assume that the particle moves nearly in synchronism with the wave, but may have some displacement ξ in the x-direction from the equilibrium orbit resulting from the particular choice of φ. Letting

$$\mathrm{Re}(kz) - \omega t = k_x\xi, \quad [13]$$

and dropping terms involving ξ^2, y^2, ξy, or a^2, the field components in the moving frame can finally be written as

$$E_x = -(Bk_0/2)(1 + 2ax)\cos\varphi - (Bk_0^2/2)(1 + 3ax)(\sin\varphi)\xi \quad [14]$$

and

$$E_y = -(Bk_0/2)[-(k_0\sin\varphi + 2a\cos\varphi) - 4ak_0x\sin\varphi]y \quad [15]$$

The corresponding equations of motion, representing respectively phase stability and transverse focussing, are

$$\ddot{\xi} = -(\eta Bk_0^2/2)(1+3ax)(\sin\varphi)\xi \quad [16]$$

and

$$\ddot{y} = -(\eta Bk_0/2)[-(k_0\sin\varphi + 2a\cos\varphi) - 4ak_0x\sin\varphi]y \quad [17]$$

Examination of these equations and Eq. [6] gives the following approximate constraints on φ, for the case $\eta < 0$ (negative ions!):

Acceleration:	$-\pi/2$	<	φ	<	$\pi/2$,
Transverse focussing:	0	<	φ	<	π,
Phase stability:	$-\pi$	<	φ	<	0.

It is apparent that all three conditions cannot be satisfied simultaneously. For the intended application, it is not essential that the beam be highly monoenergetic, and so the requirement for phase stability is not as stringent as for conventional rf accelerators. If one chooses the rf phase φ to give acceleration and transverse focussing, and gives up phase stability, one finds that the (nonlinear) equation of motion for ξ resembles that of an inverted and biased pendulum: a slightly perturbed particle rides along with the wave for a number of periods, but eventually shifts phase by 2π. For a brief time it is in a phase-region of transverse defocussing, then returns to a region of acceleration and transverse focussing. In a very long system with many stages of acceleration, particles would eventually be lost to the electrodes. However, in the fusion application mentioned in the introduction, where only modest energies are needed, the lack of phase stability might not cause any serious problems. The situation would need to be assessed on a case-by-case basis.

Acknowledgments

The authors wish to thank Klaus Halbach, Jackson Laslett, Lloyd Smith, and John Staples for helpful discussions.

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8. See, for example, G. M. Stein "Conformal Maps of Electric and Magnetic Fields in Transformers and Similar Apparatus," Chapter 4 of Construction and Application of Conformal Maps, U.S. Department of Commerce, N.B.S. Applied Mathematics Series 18 (1952). The authors thank Klaus Halbach for pointing out this method to us.