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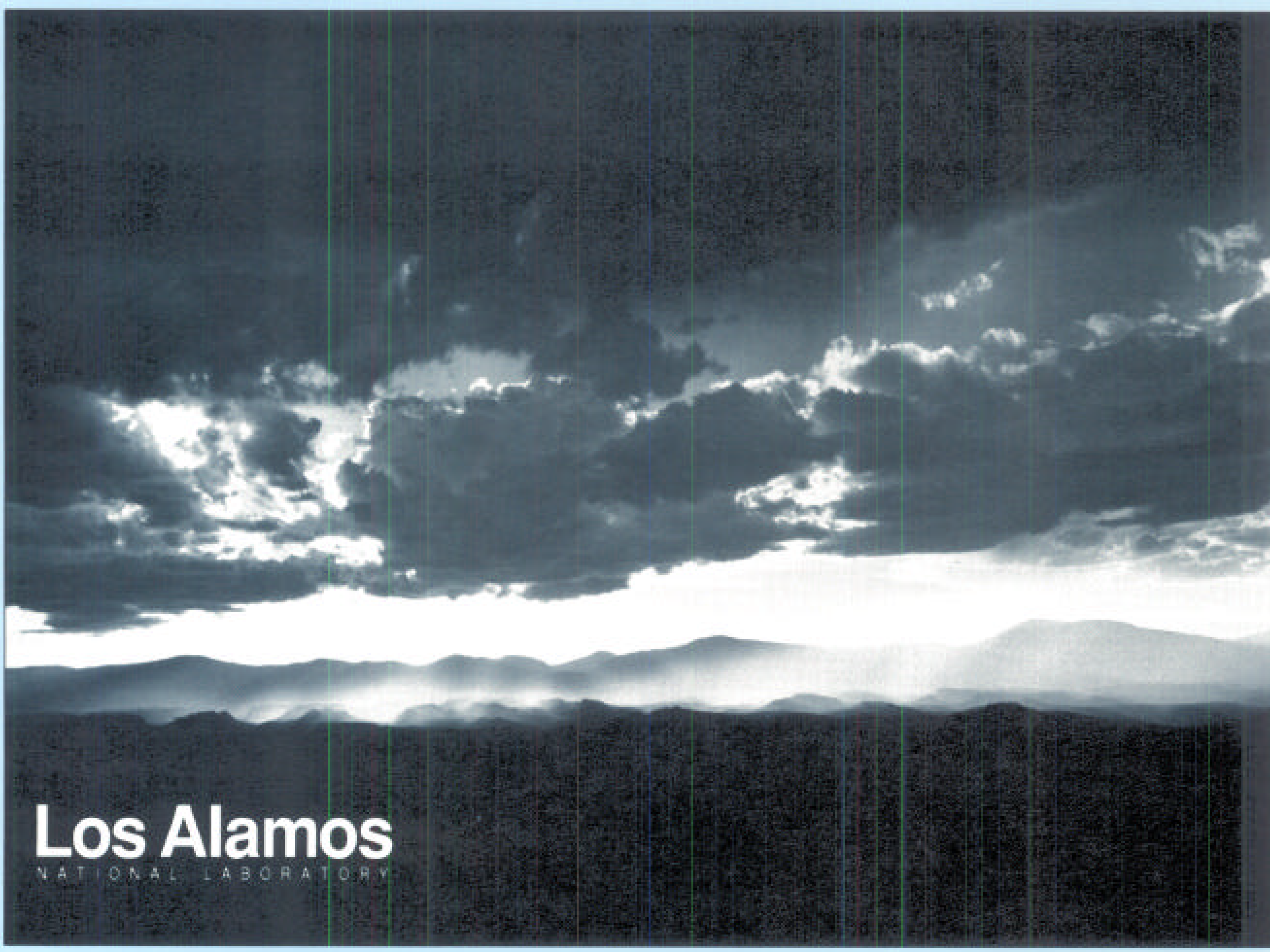

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DESIGNING DOUBLE-GAP LINEAR ACCELERATORS FOR A WIDE MASS RANGE

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Abstract

For applications like ion implantation, rf linacs using double-gap structures with external resonators can be used because they are practical at low frequencies. However, since the two gaps associated with a given resonator cannot be individually phased, it is not obvious how to build a linac that can efficiently accelerate particles having different mass/charge ratios. This paper describes the beam dynamics of double-gap rf linacs and shows how to maximize the range of mass/charge ratios. Our theory also tells us how to rescale a linac tune (i.e., reset the voltages and phases) so that a new particle, having a different mass or charge, will behave similarly to the original particle.

1 INTRODUCTION

Eaton Corporation builds high-energy ion implanters for semiconductor device fabrication. These machines are rf linear accelerators that accelerate ions to energies up to several MeV. Recently, Eaton has been working with Los Alamos to study ways to improve their machines to meet the future needs of Eaton's customers[1]. The main requirements for a near-future ion implanter linac are

- Various ion species. From $^{11}B^+$ to $^{75}As^+$.
- Variable energies. Up to several MeV.
- High current. Several mA.
- Short length. Not more than about 2 m long.

Additional requirements are low power consumption and low energy spread. This project consists of analyzing the present Eaton linac, studying new approaches for improved performance, and determining the best design based on present double-gap technology. The main part of this paper describes a new theory and design procedure, which we developed to determine the maximum performance of double-gap structures.

2 BACKGROUND

2.1 *Study of Present Eaton Machine*

The Eaton linac uses 13.56 MHz rf cells to accelerate and provide longitudinal focusing. Each cell consists of a drift tube, fed by an external helical resonator, in a grounded cavity. This provides two rf gaps per cell and is a practical way to get a compact and efficient structure at low frequencies. Electrostatic quadrupole lenses, in an alternating-gradient arrangement, provide transverse focusing. In general, accelerator performance can be limited by weak focusing, poor matching, or poor bunching. We found that the present machine has adequate focusing for accelerating $^{11}B^+$ at 3 mA but transmits only about a third of the particles injected. The losses are caused mainly by emittance growth in the rf gaps. This is a nonlinear effect caused by different particles seeing different rf phases as they cross the rf gaps. Improved bunching and matching could double the output current. To further increase the current or to get good performance for heavier ions, we need to improve the transverse focusing.

2.2 *Study of New Approaches*

New structures and focusing A single-gap rf structure (resonant cavity) has the advantage that we can phase each gap independently. We investigated the feasibility of resonant cavities at low frequencies (40 MHz). While it is possible to get a cavity of reasonable size at this frequency, we found the efficiency to be low. We studied variable-frequency radio frequency quadrupole (RFQ) structures. The high cost of variable-frequency rf power is a problem. The high transmission of most RFQ linacs is the result of adiabatic bunching. However, this is not practical for an ion implanter because of the length constraint. A segmented RFQ or an RFQ with a separate buncher may turn out to be feasible. We studied modifications to the drift tube noses in a gap structure to introduce quadrupole fields that would contribute to transverse focusing. We also studied alternating phase focusing (APF). As in previous investigations, we found that the acceptance of such machines is low.

Improved bunching A well-designed linac with a conventional (single frequency) buncher can accelerate about 75% of the particles injected. While multiple-frequency bunchers are probably not worthwhile, two separated cavities are desirable even for a single-frequency approach, because of the range of particle velocities associated with different particle masses.

Scaling studies We determined optimum quadrupole strengths and period lengths required for an alternating gradient focusing system, taking into account the defocusing effect of the rf gaps. We also verified that we can reduce the length of the linac by raising the frequency while maintaining the electrostatic and rf voltages. This is beneficial when the quadrupoles and the rf gaps are voltage (not field) limited.

3 IMPROVED DOUBLE-GAP DESIGNS

We developed a new theory (see [2] for earlier version) and design procedure for linacs having double-gap resonators and electrostatic quadrupoles. Our goal is to determine the maximum performance using technology proven at Eaton. The basic idea is that we design the linac for a certain design-reference particle. Then we scale the design-reference tune (voltages and phases) to new particles.

3.1 Theory for Double-Gap Structures

The new theory is useful for the situation in which we are voltage rather than field limited. In existing machines, power limitations limit maximum gap voltage.

In each double-gap resonator, the two gaps are separated by a distance of

$$L = \frac{\beta_o \lambda}{2\pi}(\phi_{o2} - \phi_{o1} + \pi), \tag{1}$$

where β_o is the velocity of the design-reference particle and ϕ_{o1} and ϕ_{o2} are the synchronous phases at the two gaps. As we will see, we need the flexibility to allow the two synchronous phases to be different, even for the design-reference particle.

Once the machine is designed and built, we can no longer change any of the L values, but we are free to retune the machine, i.e., to change gap voltages and phases and to inject different particles.

To see how a new particle of different mass, charge, or velocity will behave,[1] let us define some ratios, which are various quantities relative to their values for the design-reference-particle design. The focusing ratio refers to the focusing strength of the rf gaps.

$$\begin{aligned}
k_{m/q} &= \frac{m/q}{m_o/q_o} && \text{(mass/charge ratio)} \\
k_q &= \frac{q}{q_o} && \text{(charge ratio)} \\
k_\beta &= \frac{\beta}{\beta_o} = \frac{\Delta\beta}{\Delta\beta_o} && \text{(velocity ratio)} \\
k_W &= \frac{W}{W_o} = \frac{m\beta^2}{m_o\beta_o^2} && \text{(energy ratio)} \\
k_f &= \frac{1/f_e}{1/f_{eo}} && \text{(focusing ratio)} \\
k_v &= \frac{VT}{(VT)_o} && \text{(voltage ratio)}
\end{aligned} \tag{2}$$

[1] We are including the situation in which the "new" particle is the same as the design-reference particle but run at a new velocity (energy).

We assume all ratios are the same at every cell in the linac. (A constant velocity ratio β/β_o implies the velocity ratio equals the velocity-gain-per-cell ratio $\Delta\beta/\Delta\beta_o$.)

We assume all the ratios of Eq. 2, except for k_v, as given and determine the new rf voltage and phase required to achieve them. The change in energy in crossing the two gaps is given by

$$\Delta W = qeVT(\cos\phi_1 + \cos\phi_2), \tag{3}$$

where ϕ_1 and ϕ_2 are the synchronous phases on the two gaps, V is the gap voltage, and T is the transit-time factor. We assume that V and T are the same for both gaps. By evaluating Eq. 3 for both the design-reference and the new particles, and using $\Delta W = mc^2\beta\Delta\beta$, we get the following expression for the voltage ratio:

$$k_v = k_{m/q}k_\beta^2 \frac{\cos\phi_{o1} + \cos\phi_{o2}}{\cos\phi_1 + \cos\phi_2}. \quad \text{(acceleration condition)} \tag{4}$$

Once we set the phase at the first gap, the phase at the second is determined by the gap separation and the velocity.

$$\phi_2 = \phi_1 - \pi + \frac{1}{k_\beta}(\phi_{o2} - \phi_{o1} + \pi). \tag{5}$$

The effective longitudinal focusing strength (reciprocal of focal length) of the two gaps is given by

$$\frac{1}{f_e} = -\frac{2\pi qeVT}{\beta^3\lambda mc^2}(\sin\phi_1 + \sin\phi_2), \tag{6}$$

where we have added the two strengths and neglected the fact that the two gaps are separated. The focusing strength in the transverse direction is one-half of the value given by Eq. 6 and of the opposite sign. Thus the focusing ratio is the same for both transverse and longitudinal focusing.

If we compute the focusing strengths for the design-reference particle and for the other particle, take their ratio, and rearrange, we get the following expression:

$$k_f = \frac{k_v}{k_{m/q}k_\beta^3}\,\frac{\sin\phi_1 + \sin\phi_2}{\sin\phi_{o1} + \sin\phi_{o2}}. \quad \text{(focusing condition)} \tag{7}$$

If we eliminate $k_v/k_{m/q}$ in Eqs. 4 and 7, we get the following expression for how to set the phase of the first gap for the new-particle tune.

$$\tan\phi_1 = \frac{(1-c_o)k_f k_\beta S + s_o C}{(1-c_o)C - s_o k_f k_\beta S}, \tag{8}$$

where

$$\begin{aligned}
c_o &= \frac{\cos\phi_{o2} - \phi_{o1} + \pi}{k_\beta}, \\
s_o &= \frac{\sin\phi_{o2} - \phi_{o1} + \pi}{k_\beta}, \\
C &= \cos\phi_{o1} + \cos\phi_{o2}, \\
S &= \sin\phi_{o1} + \sin\phi_{o2}.
\end{aligned} \tag{9}$$

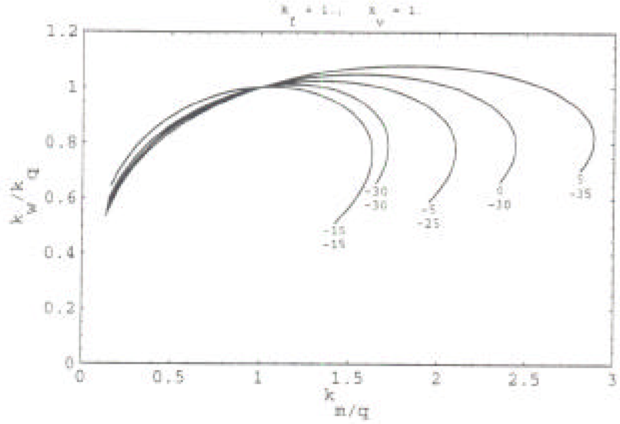

Figure 1: This shows how the energy changes when we retune a linac to a new particle. The quantity k_W is the energy ratio, k_q is the charge ratio, and $k_{m/q}$ is the charge/mass ratio. For a fixed charge, therefore, the curves show the energy as a function of mass. All ratios are relative to the design-reference particle, which is the particle for which the synchronous phases at the two gaps are ϕ_{o1} and ϕ_{o2}. The curves are labeled by the values of these phases.

Once we know ϕ_1, we determine the new voltage from Eq. 4.

Now let us determine over what range of mass/charge values a given design will work. Because we want the new particle to behave similarly to the design-reference particle, we set the focusing ratio to k_f=1. Assume our accelerator was designed to work at the maximum rf gap voltage. As a result, we want to fix the voltage ratio at k_v=1, as we cannot go any higher in voltage for the new particle. Now if we eliminate ϕ_1 in Eqs. 7 and 8, we get a relation between the velocity ratio and the mass/charge ratio, with ϕ_{o1} and ϕ_{o2} as parameters. We can rewrite this to get the energy as a function of mass. Figure 1 shows the result.

There are five curves in the figure. Each curve is labeled by the values of the synchronous phases at the two gaps for the design-reference particle, ϕ_{o1} and ϕ_{o2}. Notice the large mass range over which an accelerator with phases of (5°,-35°) can operate. The cases (-5°,-25°) and (0°,-30°) have the same rf focusing strength as (5°,-35°) but work over a more restricted range of mass values. What is happening here is that making the synchronous phase on the first gap positive reduces the distance between the two gaps, which is beneficial for heavier (slower) particles. Figure 1 shows that we can accelerate particles over a mass/charge range of about three to one to about the same energy as the design-reference particle. Quite low masses can also be accelerated, but only to somewhat lower energies.

Now consider the electrostatic quadrupoles and space charge. The quadrupoles can be set to provide the same focusing strength for the new particle by setting the voltage according to

$$qV_q/W = \text{const.}, \qquad (10)$$

where V_q is the voltage on the quadrupole electrodes.

For a focusing ratio k_f of unity, and with the quadrupoles set according to Eq. 10, the beam bunch size will be the same as for the design-reference particle if the emittance of the new particle is the same. In this case, the space-charge effects will be the same for the new particle. If we change the beam size by changing the emittance or focusing strength, we can maintain space-charge effects the same as before by adjusting the beam current.

3.2 *New Design Procedure*

We start with the TRACE 3-D code with user-defined elements for electrostatic quadrupoles and the double-gap rf cells. These elements operate in two modes. In the design mode, the code sets the rf gaps automatically to get the specified synchronous phases. Also, the quadrupole lengths and the gap voltages are automatically set to achieve the specified phase advance per focusing period in all three directions. We do this for each focusing period, getting the maximum focusing possible without exceeding the voltage limits of the gaps and taking care to avoid cell-to-cell discontinuities. In the retune mode, an existing design is retuned to a new particle according to our theory. Once we have a TRACE 3-D design, we use the PARMELA particle-tracking code to determine the fraction of the beam transmitted by the machine. We finish our design by using an optimizing version of PARMELA to fine tune the quadrupole and buncher settings. We find that our new designs have substantially improved performance while still using proven technology.

4 DISCUSSION

The new approaches need further study. However, we found that the present approach of using double-gap resonators and electrostatic quadrupoles can provide ion implanters of substantially improved performance over a wide range of mass/charge values. The design procedure we developed ensures we get the good bunching, matching, and the maximum transverse focusing. Improvements in the rf resonators could further improve performance. The rf gap voltage limitation makes it impossible to obtain significantly higher energies within the length constraint.

5 REFERENCES

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