Simultaneous Acceleration of H^+ and H^- in RFQ Linacs

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Abstract

In some cases it might be advantageous to simultaneously accelerate positive and negative beams in a radio frequency quadrupole (RFQ). Low current beams, in which space-charge forces are negligible, present no conceptual difficulty. However, when the current either in one beam or in both beams is significant, particle simulations must take into account the interaction between the two beams. A preliminary study of these effects has been completed. Two example RFQs are presented and discussed.

I. INTRODUCTION

It is sometimes advantageous to accelerate positive and negative ions simultaneously in an rf linac. Having opposite charge, the two accelerated beams can easily be separated and directed to different locations. In Drift Tube Linacs (DTL), the two beams are separated enough (180° in phase) so that there is no significant interaction between them, except in the common portion of the low energy beam transport system. Low current beams, in which space-charge forces are negligible, present no conceptual difficulties in the interaction region. However, when the current in one or both beams is significant, the interaction between the two beams must be considered.

In particular, if the initial stage of acceleration is an RFQ linac, as is now commonly the case, the interaction time between the two beams will last for many rf cycles. If both beams have equal current, the space-charge forces will initially be neutralized. As the beams begin to bunch and accelerate, the opposite charges exert forces that resist the charge separation. Although the transverse space-charge forces would be reduced over those of a single beam, the longitudinal space-charge forces would be increased. Consequently, the criteria of equal transverse and longitudinal current limits normally used in designing RFQs would probably be modified in favor of a higher longitudinal current limit.

II. SPACE-CHARGE CALCULATIONS

Accurate calculation of space-charge forces is the most difficult task in simulating particle motion in RFQ linacs. The simulation must be able to handle continuous beams, bunched beams and everything in between. A single beam is usually treated by following one group of macroparticles occupying 360° of phase. The space-charge forces are calculated by assuming that the charge distribution is periodic; that is, any number of adjacent "pulses" are assumed to have the same charge distribution as the group of particles being followed. When two beams of oppositely-charged particles are involved, the general case would be treated by following a separate group of particles for each beam. However, when the two beams have equal currents and input characteristics, the problem can be simplified by following only the positive particles. The effect of the negative beam on the positive beam is calculated by assuming that the two charge distributions are identical, but offset by 180°. The examples of the two-particle beams presented below make use of this simplifying assumption.

III. EXAMPLES

A. RFQ1

The first example is a 200 MHz RFQ designed to accelerate protons from 35 keV to 750 keV. It was designed to have equal transverse and longitudinal current limits of 100 mA and to have a normalized transverse acceptance of 0.26 π cm-mrad for a 50 mA beam. At the end of the gentle buncher, the energy was 280 keV and the synchronous phase was -35°. The average bore radius (r_0), the modulation (m) and the synchronous phase were all adjusted in the accelerator section to keep the current limits and acceptance constant.

The input beam was assumed to have a normalized rms emittance of 0.022 π cm-mrad. The input current was varied from zero to 100 mA in steps of 10 mA. The results obtained when a single beam was accelerated are compared with the results obtained when equal-current H^+ and H^- beams were accelerated. The matched input beam parameters were calculated for each current for the single beam. The matched input for the dual beams was always that of a zero-current beam because the beams were initially space-charge neutralized.

The output current and output longitudinal emittance are plotted against input current in Figures 1 and 2 for both the single and dual beams. The output transverse emittance was essentially the same for all cases, about 0.024 π cm-mrad (rms, normalized). The transmission efficiency is better for single beams at the higher currents. The output for each of the dual beams seems to level off at just below 50 mA, while the output current of the single beam is still increasing, and almost 80 mA when the input current is 100 mA. The only other difference between the single and dual beams is that the output longitudinal emittance of the dual beam is somewhat less than that of the single beam for the lower part of the current range.

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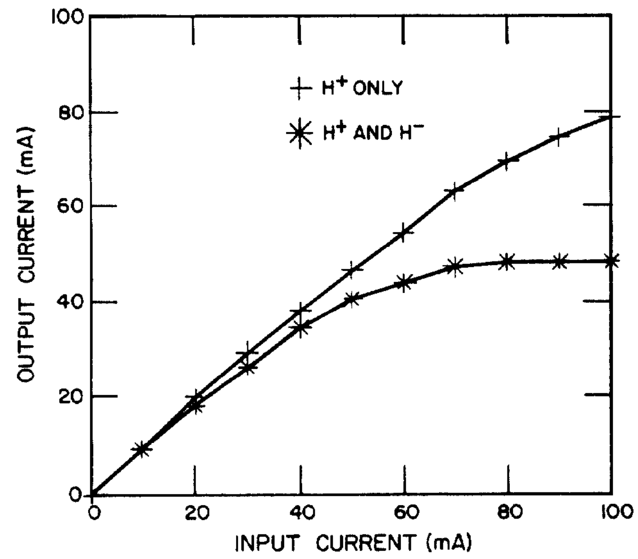

Figure 1. Output current from RFQ1 versus input current when only H^+ is accelerated (+) and when H^+ and H^- are simultaneously accelerated (*).

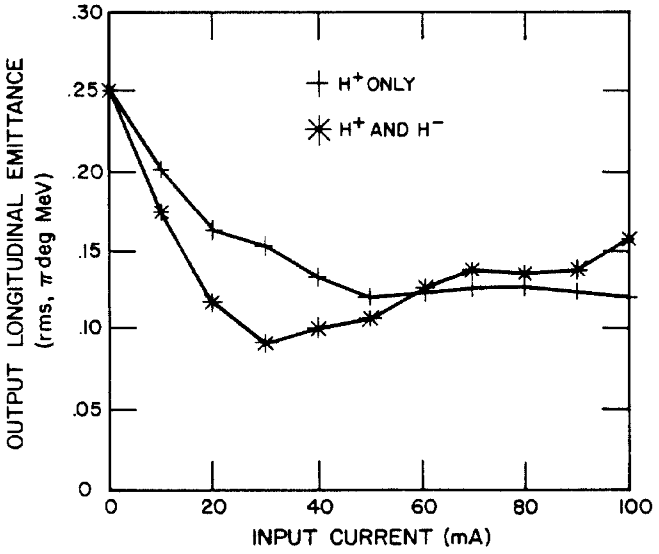

Figure 2. Output longitudinal emittance (rms) from RFQ 1 versus input current when only H^+ is accelerated (+) and when H^+ and H^- are simultaneously accelerated (*).

B. RFQ2

The second example RFQ has the same vane voltage, injection energy and initial aperture as RFQ1, but the longitudinal current limit was increased to 145 mA at the end of the gentle buncher, while the transverse current limit was 97 mA. The energy at the end of the gentle buncher was 220 keV and the synchronous phase was -40°. The synchronous phase and r_0 were kept constant in the accelerator section, while m was ramped from 2.15 to 2.30.

The estimated normalized acceptance stayed nearly constant, around 0.25 π cm-mrad, and the transverse and longitudinal current limits both increased in the accelerator section to about 170 mA. As might be expected, the transmission of the dual beams through RFQ2 is better than through RFQ1, as shown in Figure 3. The longitudinal emittance output from RFQ2, shown in Figure 4, is similar to that of RFQ1.

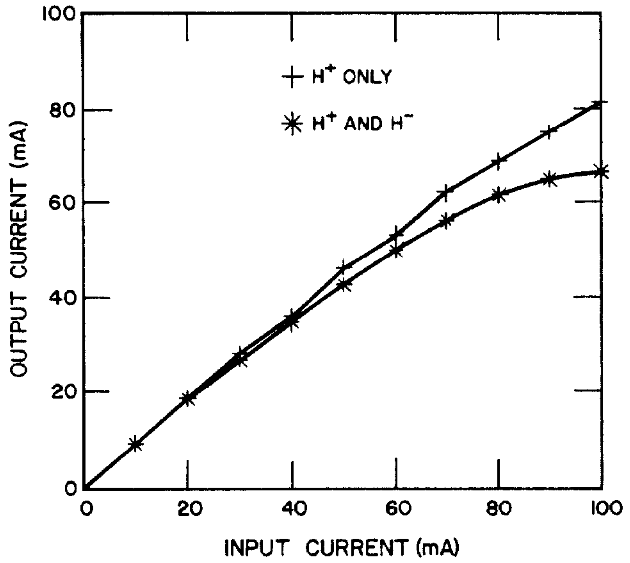

Figure 3. Output current from RFQ2 versus input current when only H^+ is accelerated (+) and when H^+ and H^- are simultaneously accelerated (*).

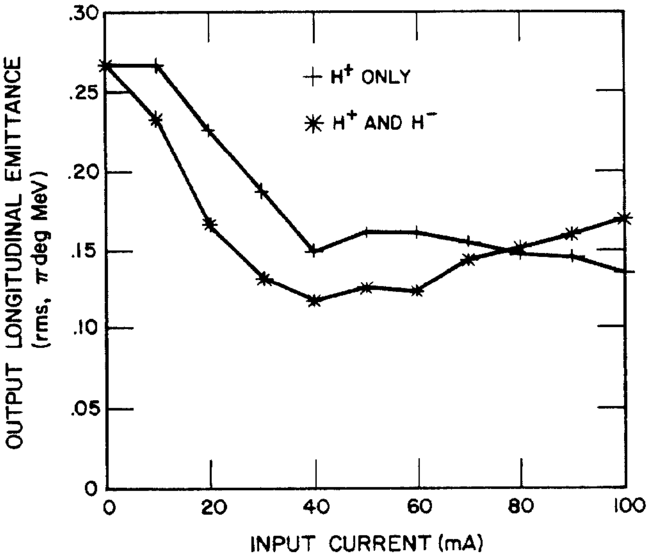

Figure 4. Output longitudinal emittance (rms) from RFQ2 versus input current when only H^+ is accelerated (+) and when H^+ and H^- are simultaneously accelerated (*).

IV. RFQ OUTPUT BEAM

The oppositely-charged beams exiting the RFQ are easily separated with a bending magnet, but are not so easily matched into a common magnetic transport system or into a DTL. In the RFQ, the beams are kept focused by an alternating electric quadrupole field. During a positive half cycle of the rf, when the horizontal vanes have a positive potential and the vertical vanes have a negative potential, the positive beam is focused in the horizontal direction and defocused in the vertical direction, while the negative beam is focused vertically and defocused horizontally. During the negative half cycle, the situation is reversed: the positive beam is defocused horizontally and the negative beam is focused horizontally. The alternating longitudinal fields in the RFQ cause the two beams to be separated longitudinally by half of the rf cycle. If the positive beam exits the RFQ after a positive half cycle, the negative beam will exit after a negative half cycle. Each beam will just have experienced a horizontally focusing field and would be ready to see a vertically focusing field, which of course cannot be supplied by the same magnetic quadrupole. Consequently, if the two beams were to be matched into a common DTL, a relatively complicated "transition region" would be needed. If two separate RFQs are used, one RFQ could have the ripples on its horizontal and vertical vanes interchanged. Then the two beams would exit after having been focused in opposite planes, and each beam would be ready to pass through the same sequence of quadrupole magnets.

V. CONCLUSIONS

The beam dynamics calculations presented here show that there is no fundamental reason why positive and negative beams cannot be accelerated simultaneously in an RFQ linac. These results do reveal that the design criteria should be modified to give a larger longitudinal current limit for such an RFQ. The decision on whether to use one or two RFQs when accelerating positive and negative beams for injection into a drift tube linac would depend on several considerations: economics; the difficulty of matching two separate low energy beams into the same RFQ; and the difficulty of matching the output beams into a magnetic focusing system.