APPLICATION OF THE RF QUADRUPOLE IN LINEAR ACCELERATORS FOR HEAVY ION FUSION*

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ABSTRACT

The rf quadrupole (RFQ) linac structure is proposed as an alternative to a system composed of a buncher and independently phased cavities in the low-velocity acceleration section. Beam dynamics simulation studies have demonstrated that with the RFQ (1) high transmission and low beam loss are possible, (2) it is possible to use a low voltage 0.25 MV dc injector and still obtain high output beam currents, (3) the current required from the injector is reduced because of the high transmission of the RFQ, and (4) the output emittance appears to be at least comparable to that expected from a buncher and independently phased cavities.

INTRODUCTION

The low-velocity accelerator is an important element in heavy ion drivers for inertial confinement fusion. It is widely recognized that beam intensity limitations and radial emittance growth tend to occur predominantly at low velocities in linear accelerator systems. The characteristics of the RFQ make it an attractive alternative approach to other designs that have been proposed. One proposal[1,2,3] is to use a high voltage dc injector to accelerate a heavy-ion beam, for example Xe^{+1}, from the ion source to about 1.5 MeV. This is followed by an rf buncher and several independently phased cavities with magnetic quadrupoles between the cavities. At about 2.3 MeV, the Xenon beam is injected into a sequence of three Wideröe linacs and accelerated to an energy of about 20 MeV. This arrangement provides for acceleration of about 20 to 25 mA of Xe under current-saturated conditions. It is argued[3] that the high voltage of the dc injector is desired in order to obtain a high current limit and a higher starting frequency (12.5 MHz) as compared with other possible schemes which use a lower voltage injector. In this paper we suggest an alternative approach,

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which would use the RFQ to accept the injector beam, bunch it and accelerate it to a few MeV. A major advantage of the RFQ is that a much lower voltage injector (⩽250 kV) can be used without lowering the space charge limit. In addition, the RFQ has the potential for adiabatic bunching, which can result in capture efficiencies in excess of 90% and minimal brightness reduction. Furthermore, as pointed out by Swenson,[4] the RFQ lends itself to array-like configurations that can be used to increase the total beam intensity. The bunches from the different beam channels in the array can easily be combined so as to interlace longitudinally, as is desirable when funneling prior to a frequency transition.

The RFQ can operate at lower beta than conventional drift tube linacs because the focusing is obtained from the rf electric fields so there is no requirement to include magnetic quadrupoles within the small cells. This opportunity to use a linear accelerator at low beta values permits adiabatic bunching of the dc beam, resulting in high capture and transmission efficiencies (>90%). Adiabatic bunching is not restricted to low energies in principle, but its application at higher energies can become very costly in length. Good transmission efficiency implies small beam loss. Reducing the amount of lost beam, and keeping the energy of lost particles low, may be important in order to minimize potential problems associated with localized heating of components by an intense beam.

RFQ Design

The LASL RFQ design approach has been reported previously.[5,6] In the most general case, it consists of combining four sections called the radial matching section, the shaper, the gentle buncher and the accelerator section. The adiabatic bunching is done in the shaper and gentle buncher sections. The synchronous phase angle is ramped from -90° to its final value at the end of the gentle buncher, so the beam reaches its minimum phase extent at this point. For this and other reasons the space charge limit typically does not occur for the dc beam at the input, but instead occurs at the end of the gentle buncher.[7] In the case where the focusing force is restricted by the maximum obtainable electric field, for a given aperture size the current limit is found to scale approximately as

$$I \propto \frac{q}{A} E_s^2 \beta \lambda^2 \quad (1)$$

where q and A are the charge state and mass number of the ion, E_s is the maximum surface electric field, βc is the ion velocity at the end of the gentle buncher, and λ is the rf wavelength. One can also show that the length of the gentle buncher section, for a fixed energy gain ratio within the section, scales as

$$L \propto \frac{A}{q} \frac{\beta^3 \lambda}{E_s} \tag{2}$$

The length formulas for the shaper and accelerator sections are similar to Eq. (2). These formulas show that the current limit increases in proportion to β but the length increases in proportion to β^3. Thus the advantage of high energy, which raises the current limit, is soon offset by a rapidly increased structure length.

RFQ Linacs for Heavy Ions

We now present two examples of RFQ linac designs for singly charged Xenon. The first demonstrates acceleration under a current-saturated condition, which is always accompanied by high beam losses and an output emittance characterized by the geometric acceptance of the channel. The output emittance in this case is kept small by using a small bore. The second example illustrates acceleration under more lightly-loaded conditions where a smaller fraction of the input current is lost.

Both examples contain the three sections mentioned earlier, the shaper, the gentle buncher and an accelerator section. The gentle-buncher initial and final energies were chosen to be 0.25 MeV and 2.5 MeV respectively. These choices represent a compromise between good performance for high beam currents and overall length. Then the initial energy, where the shaper section begins, was chosen to be 0.242 MeV in accordance with our standard design approach.[6] A final energy of 5 MeV is arbitrary and could be increased without adding greatly to the length. A maximum surface field was assumed to be E_s = 15 MV/m, which we regard as a conservative operating point.

The computer program that we use to study the RFQ beam dynamics is called PARMTEQ[6] (a modified version of PARMILA). For the input we used a zero energy spread dc beam, whose initial transverse phase space distribution was generated by uniformly filling the volume of a 4-dimensional hyper-ellipsoid. The normalized input emittances in both x,x' and y,y' phase space, which contain 100% of the beam, were taken to be 0.01π cm-mr. This results in 90% of the input beam within 0.007π cm-mr, and an rms input emittance of 0.0017π cm-mr.

Table I is a summary of the parameters for the two cases. The frequency is 12.5 MHz and the synchronous phase begins at -90° and ends at -32° in both cases. The initial and final vane modulation parameters m_i and m_f are listed.[5,6] V is the intervane voltage and r_o is the average radius parameter, which is equal to the initial radial aperture. The length L for both cases includes a radial matching section at the input. An important difference between linacs 1 and 2 is the aperture difference as is indicated by r_o. Notice also that although linac 2 has a larger voltage than linac 1, it is longer because of its smaller vane modulation parameter m.

Table II shows the results for linac 1 at four input beam currents. The entries include average input current, I_i, average output current I_o, and transmission efficiency T. The normalized output transverse emittance at the 90% contour is ε_{90}, and the rms normalized output emittance is ε_{rms}. Linac 1 is operated essentially at its saturated current limit of slightly more than 20 mA for input current values larger than 30 mA. The aperture limits the final normalized emittance to a relatively small value. The transmission at I_i = 30 mA of 74.7% is still higher than most conventional single gap buncher configurations.

Table III shows some results obtained for linac 2 for four input beam currents. The aperture of linac 2 is larger than linac 1 and consequently its acceptance is greater. In contrast to linac 1 there is almost no restriction caused by the aperture at I_i = 30 mA. This results in a high transmission (96.9%) and a larger output emittance (ε_{90} = 0.031π cm-mr) than for linac 1. As the input current increases we observe the expected decrease in transmission. For input currents of 40 and 50 mA, the output current approaches its saturated limit at a value greater than 30 mA.

We see from the linac 1 results that, as might be expected, it is possible to obtain a high current beam with a small output emittance at the cost of reduced transmission. However, linac 2 probably best illustrates the advantages of the RFQ. For input currents less than 30 mA it captures and transmits nearly all of the injected beam and thereby minimizes any problems associated with beam losses. The output transverse emittance ε_{90} at 5 MeV obtained from the simulation code for $I_i \leqslant 30$ mA is consistent with the estimate assumed in design studies using the beam from the alternative buncher-independently phased cavity system.[8] For linac 2 at I_i = 30 mA we calculate a two-dimensional output brightness of B = 6.1 A/cm^2-mr^2, where we have defined the brightness as $B = 2I/\pi^2\varepsilon_{90}{}^2$. In addition, we have calculated the longitudinal output emittance at the 90% contour and we obtain a value of 0.85π MeV-deg.

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TABLE I

RFQ PARAMETERS

Linac	1	2
q	1	1
Ion	^{132}Xe	^{132}Xe
f(MHz)	12.5	12.5
W_i(MeV)	0.242	0.242
W_f(MeV)	5.0	5.0
ϕ_i(deg)	-90	-90
ϕ_f(deg)	-32	-32
m_i	1.00	1.00
m_f	2.00	1.48
V(MV)	0.134	0.200
r_o(cm)	1.22	1.81
L(m)	23.3	27.1

TABLE II

LINAC 1 RESULTS

I_i(mA)	I_o(mA)	T(%)	ε_{90}(cm-mr)/π	ε_{rms}(cm-mr)/π
20	18.8	93.9	0.015	0.0032
30	22.4	74.7	0.018	0.0038
40	22.4	56.1	0.021	0.0045
50	21.1	42.2	0.021	0.0045

TABLE III

LINAC 2 RESULTS

I_i(mA)	I_o(mA)	T(%)	ε_{90}(cm-mr)/π	ε_{rms}(cm-mr)/π
20	19.9	99.7	0.027	0.0056
30	29.1	96.9	0.031	0.0068
40	33.8	84.4	0.037	0.0077
50	33.9	67.8	0.041	0.0085

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