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TITLE: THE RADIO-FREQUENCY-QUADRUPOLE LINAC IN A HEAVY ION FUSION DRIVER SYSTEM

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The Radio-Frequency Quadrupole Linac in a Heavy-Ion Fusion Driver System*

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Summary

A new type of linear accelerator, the radio-frequency quadrupole (RFQ) linac, is being developed for the acceleration of low-velocity ions. The RFQ accelerator can be adapted to any ion species, and it is particularly suitable for high-current applications. A recent experimental test carried out at the Los Alamos Scientific Laboratory (LASL) has demonstrated the outstanding properties of RFQ systems. The test linac accepts a 30-mA proton beam of 100-keV energy and focuses, bunches, and accelerates the beam to an energy to 640 keV. This is done in a length of 1.1 m, with a transmission efficiency of 87% and with a radial emittance growth of less than 60%. The proven capability of the RFQ linac, when extended to heavy ion acceleration, should provide an ideal technique for use in the low-velocity portion of a heavy-ion linac for inertial-confinement fusion. A specific concept for such an RFQ-based system is described.

Introduction

The low-velocity portion of an rf linac is an important element in heavy-ion drivers for inertial-confinement fusion. Beam intensity limitations as well as most of the radial emittance growth tend to occur in the low-velocity sections. Optimizing the design at low velocities allows the remainder of the linac to be more efficiently designed. The conventional solution for low-velocity heavy ions is to use a large electrostatic injector of perhaps 1.5-MV potential followed by a buncher and special linac structures. A new approach to the acceleration of low-velocity ions is being developed by LASL. This method uses the RFQ linear accelerating structure to accept a dc beam from an ion source, and then to bunch and accelerate it to a high enough energy to allow the use of conventional methods for further acceleration. Use of the RFQ linac can eliminate the need for a high-voltage dc injector because beams with ion-source energies can often be directly introduced into the RFQ linac.

Kapchinskii and Teplyakov first proposed the RFQ principle in 1970.[1] Except for some tests in the USSR, the RFQ concept was neglected until 1978, when its development was initiated by the LASL Accelerator Technology Division.[2,3,4,5]

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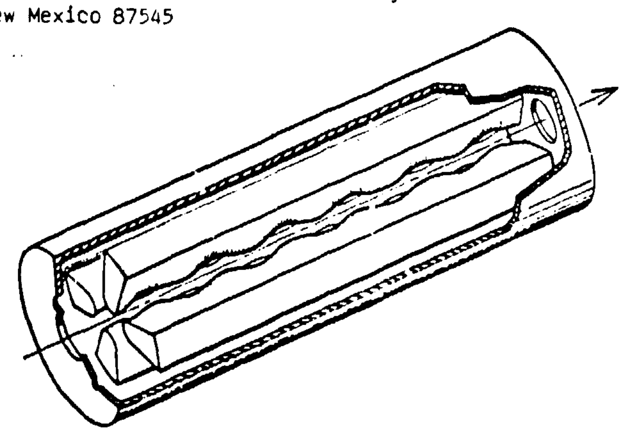


Fig. 1. RFQ Four-Vane Resonator Structure.

RFQ Principles and Beam Dynamics

The RFQ linac uses transverse electric fields to focus ions traveling along its axial region. Figure 1 is a schematic drawing of a small section of an RFQ 4-vane resonator. The resonator produces rf voltages on the vanes, and a strong focusing quadrupole force is impressed on the ions that travel along the axial region of the resonator. To produce longitudinal electric forces for ion acceleration, the pole tips are periodically modulated, as shown in the figure. Figure 2 shows a cross section of the RFQ pole tips in the x-z plane. In the y-z plane, the pole tips also have mirror symmetry but are shifted relative to the poles in the x-z plane by $\beta\lambda/2$.

The beam-dynamics design of an RFQ system has several objectives. First, the input dc beam is allowed to adapt itself to the time-varying radial focusing forces. To do this, the pole tips are shaped to gradually turn on the focusing strength over a distance of $5\ \beta\lambda$. Next, the accelerating force is turned on by slowly increasing the periodic modulation on the pole tips. This allows the beam to be adiabatically bunched in a manner that minimizes radial emittance growth and maximizes capture of the input beam. After the bunching is completed, the beam is accelerated to a final energy that is sufficiently high to allow the beam to be directly injected into a conventional rf linac for further acceleration. In most linear

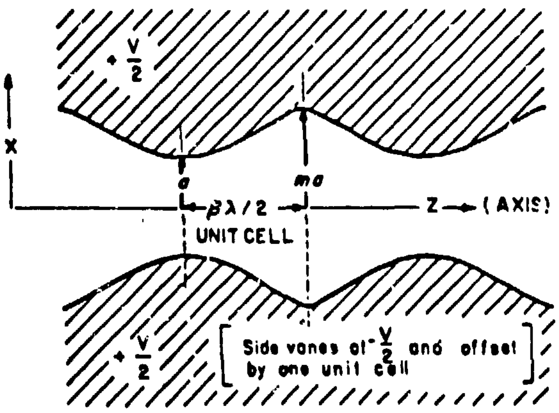


Fig. 2. RFQ Vane Tip Geometry
a = radius parameter
m = radius modulation parameter
βλ = cell length

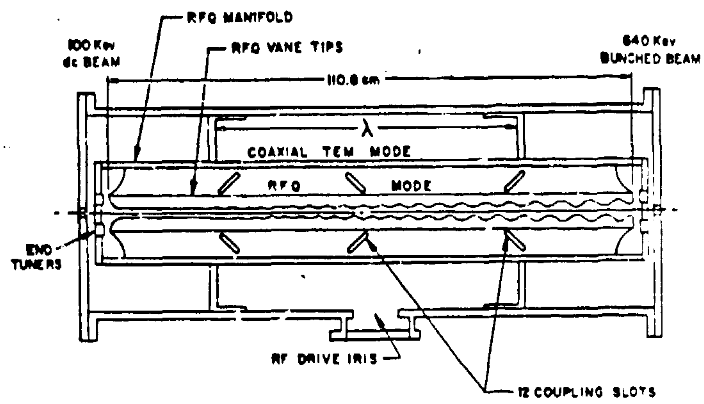
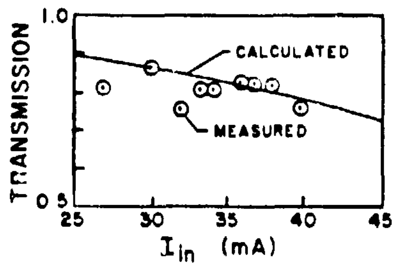
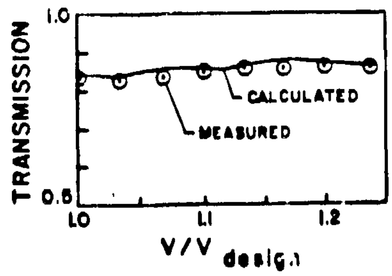


Fig. 3. RFQ POP Schematic.



(a) Transmission vs input beam current.



(b) Transmission vs vane tip voltage.
Fig. 4. RFQ POP Measured vs Calculated Parameters.

accelerators, the current-carrying capacity is determined by conditions at the input where the beam is already bunched. In contrast, an RFQ linac bunches the beam to its final configuration only after the energy has been increased by a factor of ~10. This means that the current capacity of an RFQ system has a higher value characteristic of this higher energy.

To illustrate the use for heavy ions, an RFQ linac has been designed to accelerate Xe^{+1} ions from 0.1 to 6.0 MeV. This RFQ operates with a frequency of 12.5 MHz, has a current of 25 mA, and is 12 m long. For use in a heavy-ion fusion driver, the linac can be constructed in the form of a 4-channel array. The 25 mA beams from the individual channels can be combined using techniques described elsewhere in this paper.

RFQ POP Results

One of the applications of the RFQ under consideration at LASL is for the high-intensity 35-MeV 80-MHz deuteron accelerator being designed for the Hanford Fusion Materials Irradiation Test (FMIT) Facility. An essential step in evaluation of the RFQ for this accelerator was a full power test called the RFQ proof of principle (POP) experiment.

The 425-MHz RFQ POP experiment (illustrated in Fig. 3) accepts a nominal 30-mA beam of 100-keV protons and produces a focused, bunched and accelerated 640-keV beam in 110.8 cm. It was recognized that a test of an RFQ linac at 425 MHz (the frequency of an existing klystron) would be a very stringent test of the principles involved. The final energy, capture efficiency, and emittance growth were studied as a function of the input beam current and the rf field level. These measurements[4] have shown that the RFQ performs near the levels predicted by the beam dynamics calculations.[4,5] The measured and calculated transmission for different injected beam currents are shown in Fig. 4a. Figure 4b shows the results of the calculated and measured transmission for different RFQ vane voltages with a 37-mA injected beam. This 425-MHz RFQ has operated reliably at rf fields 35% greater than the design value, and consistantly accelerated more than 80% of a 38-mA proton beam injected at 100 keV to a final energy of 640 keV. Analysis of the data indicates that the emittance growth is less than 60%.

Application of the RFQ Linac to Heavy Ion Fusion

The radio-frequency linac can generate high-current, high-energy beams of heavy ions for inertial fusion applications. A conceptual design[6,7] has shown how Xenon ions can be accelerated to form a 10 GeV final beam with a current of 0.8 A. This design emphasized acceleration in high-frequency magnetically-focused linacs where the efficiency for transfer of rf power to the beam can be high. It was shown that to fill the high-frequency linacs with the high currents that they are capable of accelerating, a technique called "funneling" can be used. This scheme combines and interlaces pulses from two linacs with frequency f into a single beam of twice the current that then can be accelerated in the next linac stage operating with frequency 2f. Repeated application of funneling maximizes the efficiency by filling every phase stable bucket in every linac.

This conceptual design begins with 32 RFQ linacs operating with a frequency of 12.5 MHz. Through repeated applications of funneling, it ends with a single 0.8A beam of that is accelerated to 10 GeV in the final magnetically focused drift tube linac operating with a frequency of 800 MHz. It is proposed that the 32 RFQ linacs be constructed in 8 modular arrays, each consisting of 4 RFQ channels. Figure 5 shows one of these modules and emphasizes the close lateral spacing of the channels that facilitates combining pairs of beams by funneling. Relative to each other, the two channels whose beams are to be funneled would be shifted longitudinally a distance equal to their final value of $\beta\lambda/2$. This allows use of a symmetric deflection system to combine and interlace the microstructure pulses.

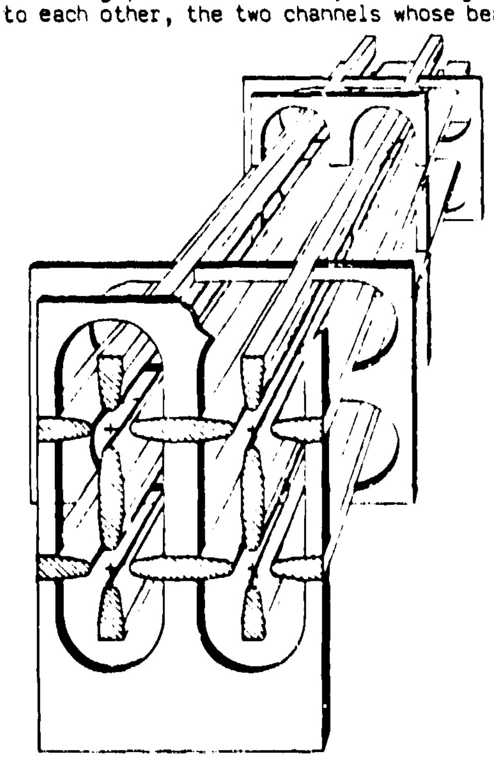


Fig. 5. RFQ Array.

Conclusion

The RFQ linac has many characteristics that make it an excellent choice for the acceleration of low-velocity ions. It allows the use of a low-voltage dc injector, has a high current capability, and produces minimal radial emittance growth. Also, it can be constructed in the form of closely-packed multichannel arrays that facilitate the use of funneling techniques. These properties make the RFQ linac an attractive choice for the first stage of an rf linear driver accelerator for heavy ion fusion.

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