# LOW FREQUENCY RFQ LINACS FOR HEAVY ION FUSION*

A. Moretti, J. M. Watson, R. L. Martin, R. J. Lari and R. L. Stockley
Argonne National Laboratory
Argonne, Illinois

## Summary

Low frequency, radio frequency quadrupole (RFQ) structures are under study at Argonne National Laboratory (ANL) as the low-velocity portion of an rf linac driver for heavy ion inertial confinement fusion. Besides offering a direct comparison with the present ANL front end, it would provide a second low-velocity $Xe^{+1}$ linac for funneling experiments at 22.9 MeV. Heavy ion RFQ accelerators are characterized by their low rf operating frequency of about 10 MHz. The large size of a manifold-fed four-vane, 10 MHz RFQ resonator structure (about 6 m in diameter) makes it unacceptable for heavy ions; therefore, alternate structures are under study at Argonne. The structures under study are: (1) a Wideroe-type structure with external stub lines, (2) a Wideroe-type structure with the stub lines internal to the structure, (3) a split coaxial line resonator with modulated vanes, and (4) a interdigital line resonator with modulated cylindrical rods. The split coaxial line resonator seems best at this low frequency. It is compact and very efficient. About 15.5 m of linac structure excited with 560 kW of rf power is sufficient to accelerate 30 mA of $Xe^{+1}$ with 97% transmission efficiency from 250 keV to 3 MeV.

## Introduction

An RFQ linac[1,2] is a structure which has four-pole symmetry and produces focusing, bunching, and acceleration of charged particle beams by the use of radio frequency electric fields only. No internal static magnetic or electric quadrupoles are required in the structure proper, as is the case with a conventional rf linac. The four-pole symmetry of the device produces a strong electric quadrupole field in the vicinity of the beam aperture which can be used to focus and confine low beta charged particle beams. Because the beam focusing is performed by the rf electric field, it is possible to produce strong focusing forces in the low beta region where conventional quadrupole magnets are not feasible. It is the strongest known low beta focusing structure.[3] By modulating the pole pieces a longitudinal component of electric field is produced which is used to bunch and accelerate the beam. Proper shaping of the rf "focusing" lattice, bunching section and accelerating section results in a linac capable of accelerating particles of low injection energy to moderately high output energy levels with greater than 90% capture efficiency for high beam current inputs.[3]

## Structures

The problem with the use of the four-vane RFQ resonator developed at LANL at the low frequencies required for heavy ions is its large size, 6 m in diameter at 10 MHz. Therefore, alternate, more economical structures have been under study at ANL and elsewhere.[4,5]

The structures that we have been examining are shown in Figs. 1, 2, and 3. Figure 1 shows the design of a Wideroe-type linac cavity (RFQ Structure #1) with four external stub lines. Two of the modulated vanes are supported by the stub lines and are driven at the same potential by separate rf feed loops. The other two modulated vanes are grounded to the outside shell, dividing the structure into two electrically symmetric halves. Each half can then be looked at as a separate Wideroe tank with heavy capacitive loading. Figure 2 shows the design of a Wideroe-type linac cavity (RFQ Structure #2) with four "internal" stub lines. As was the case with the previous design two modulated vanes are supported by the stub lines and are driven at the same potential by separate rf feed loops. The other two modulated vanes are grounded to the outside shell, dividing the structure into electrically symmetric halves. Figure 3 shows the design of the split coaxial resonator (RFQ Structure #3). It has four blade-shaped beams or electrodes supporting the RFQ modulated vanes. Two diametrically opposite beams are grounded to the end plate at one end of the structure, while the other two are grounded at the other end. This can be looked at as a interdigital filter with strong capacitive coupling. It is similar to the GSI design.[6] However, instead of real drift tubes and fingers, it uses the LANL modulated vanes to produce the required RFQ fields. A fourth structure, a variation of structure #3 is possible. It uses modulated cylindrical rods in place of the blade-shaped support electrodes and LANL modulated vanes. However, the study of its performance characteristics is incomplete and will not be further reported on in this paper. One would however expect it to perform about as well as structure #3, but not be as mechanically rigid.

Structures #1 and #2 were analyzed using a transmission line model. The computer program POISSON[7] was used to determine the inter-electrode capacitance of the vane tips and hence the loading of the transmission line. The length of the structure is determined by the amount of voltage variation allowed along the line. In the case studied only 10% variation was allowed, which gives resonant structure lengths of 4 m and 5 m for structures #1 and #2, respectively. Table I gives some of the performance parameters for the ANL 6 RFQ design.[8] As can be seen, four Type #1 structures or three Type #2 structures are required to accomplish the approximate 15.5 m of structure required. The modulated vanes can be made continuous from one structure to the next by cutting holes in the end plates at the open circuit point, thus allowing no interuptions in the modulation of the vanes. The structures can be excited

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separately or from a single source by coupling the structures together by additional slots in the end plates, thus running them as a super cavity.

Structure #3 was analyzed as a multi-conductor transmission line.[9] The voltage and current along a multi-conductor line are given by the matrix equations

$$[V] = [V_0] \cos \beta\ell + j\,[G]^{-1}\,[I_0] \sin \beta\ell$$

and

$$[I] + [I_0] \cos \beta\ell + j\,[G]\,[V_0] \sin \beta\ell$$

where

$$[G] = [C]/(\mu\varepsilon)^{1/2}$$

and [C] is the distributed capacitance matrix. Using these relationships and proper terminating conditions, it can be shown that the resonant condition for a uniform line is given by

$$\cos^{-1} \beta\ell = 2\,C_{12}/C_{11}$$

where

$C_{12}$ is the capacitance between conductors,
$C_{11}$ is capacitance of a conductor to all other conductors and ground
$\beta = 2\pi/\lambda$ and $\ell$ is length of structure

The results of this analysis agree with those using the GSI relationships[6] and are also shown in Table I.

A model of structure #3 was constructed to test the derived relationship and is shown in Fig. 4. The outside shell is made of an aluminum tube 0.19 m in diameter and 0.5 m long. The blades are supported by copper rods 0.019 m od and 0.48 m long. They are placed 90° apart on a 0.038 m diameter circle. POISSON was used to calculate $C_{12}$ and $C_{11}$. The measured frequency of 58 MHz agreed to within a few percent of the calculated value using the above relationship.

## Conclusion

The split coaxial resonator RFQ is a compact and efficient RFQ design for a low frequency heavy ion linac. A structure 1.2 m in diameter and 2 m long resonates at 12.5 MHz. Eight structures requiring about 560 kW of input rf power are sufficient to satisfy the requirements of the ANL 6 design (accelerate 30 mA of $Xe^{+1}$ with 97% transmission efficiency from 250 keV to 3.0 MeV). The structures need to be placed close together so that the modulated vanes are not interrupted. The Wideroe-type structures are more complicated and more difficult to build. Hence, they are less attractive for heavy ions.

## TABLE I

### Parameters for ANL 6 Design

Beam Current = 30 mA $Xe^{+1}$
Transmission Efficiency = 97%
$W_i$ = 250 keV; $W_{out}$ = 3.0 MeV
$\varepsilon_{in}$ = 0.0136π cm mr, normalized
$\varepsilon_{out}$ = 0.038π cm mr, normalized
Intervane Voltage = 211 kV
Total Length = 15.5 m
Structure Diam. = 1.2 m

| LINAC TYPE | LENGTH OF ONE STRUCTURE | NO. OF STRUCTURES REQUIRED | TOTAL POWER REQUIRED |
|---|---|---|---|
| #1 Wid. Ext. Stub Line | 4 m | 4 | 560 KW |
| #2 Wid. Int. Stub Line | 5 m | 3 | 900 KW |
| Split Coax. Resonators | 2 m | 8 | 560 KW |

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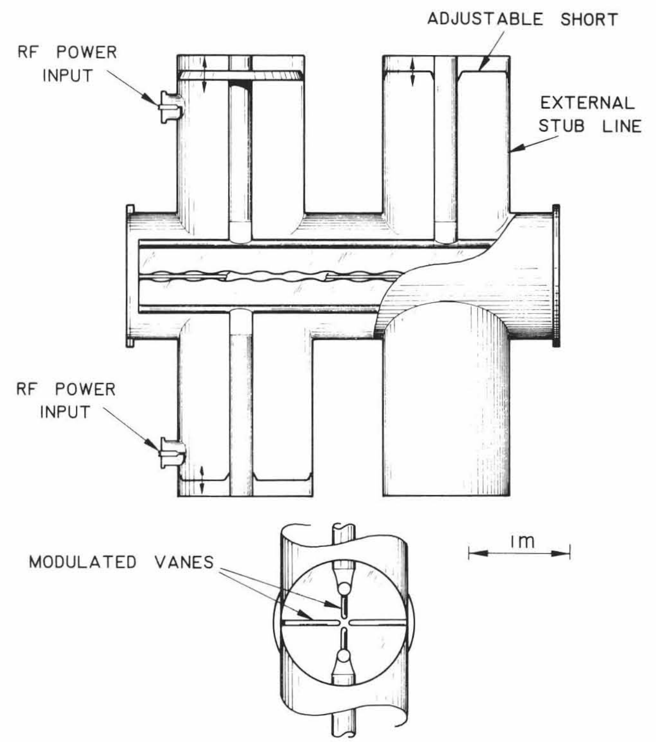

Figure 1 - A 12.5 MHz Wideroe-Type RFQ Structure with External Stub Lines

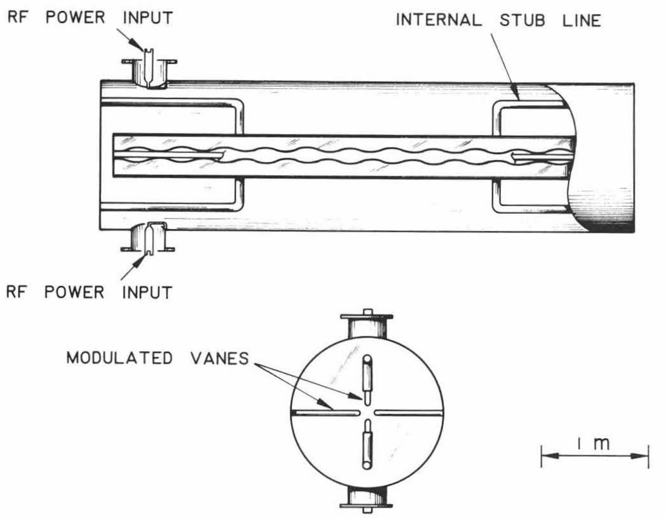

Figure 2 - A 12.5 MHz Wideroe-Type RFQ Structure with Internal Stub Lines

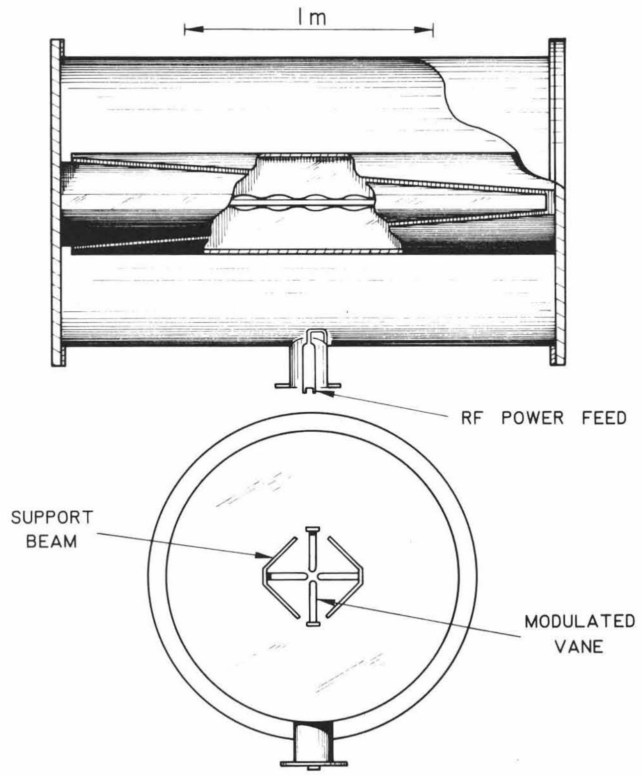

Figure 3 - A 12.5 MHz Split Coaxial Line RFQ Structure with Modulated Vanes

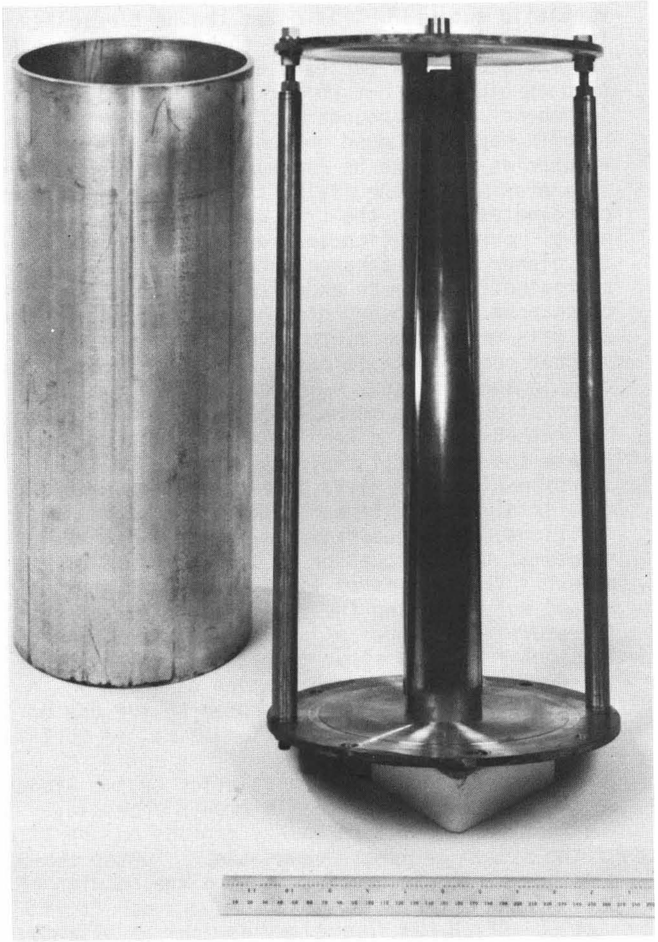

Figure 4 - Model of Split Coaxial Line RFQ Structure