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RADIO FREQUENCY QUADRUPOLE ACCELERATING STRUCTURE RESEARCH AT LOS ALAMOS*

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Abstract

The results of studies of radio frequency quadrupole accelerating structures are presented. Measurements indicate that this is a promising structure for transporting and accelerating ion beams in the energy region of 50 KeV to 2 MeV.

Basic Concepts

The radio frequency quadrupole (RFQ) accelerator serves two functions as a low energy accelerator. First, it converts DC beam from an ion source into a bunched beam acceptable to a drift tube linac. Second, it accelerates the beam from the ion source output energy up to the energy required for injection into a drift tube system.

The RFQ simplifies injector design by accepting beam at a lower energy than a drift tube linac. Problems with the design of the low energy end of a drift tube linac are precluded because the RFQ can accelerate the beam to higher energies than are feasible with conventional injectors.

A series of low power RFQ models are being studied in preparation for a powered test in which an ion beam is accelerated. The hot test will be conducted at 440 MHz on the PIGMI test stand and will be considered the engineering proof-of-principle for the RFQ.

Focusing

Normally linear accelerators use periodically spaced quadrupole magnets as focusing elements. The RFQ focuses with electrostatic quadrupole fields which are uniform all along the beam channel. Figure 1 shows an arrangement of four conducting lines around an axis. Off-axis particles in such a structure experience focusing in one plane and defocusing in the other and vice versa on alternate RF half-cycles. The result is a strong focusing system which will transport a beam without acceleration along the axis.

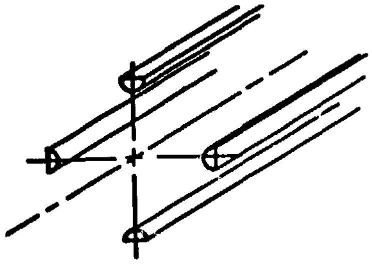

Fig. 1.
Four conductor line.

Acceleration

Longitudinal acceleration occurs because of a mechanical perturbation on the four line electrostatic focuser. If the distance between electrodes of similar polarity varies periodically along the beam channel, as shown in Fig. 2, a longitudinal field results. Since the polarity of E_z alternates in each gap, the RFQ is a $\beta\lambda/2$ structure.

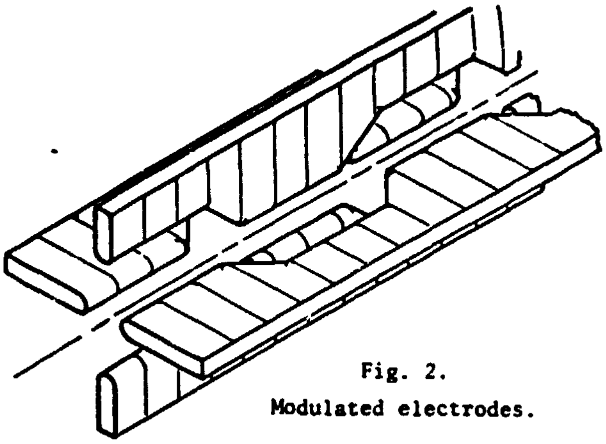

Fig. 2.
Modulated electrodes.

Evolution of the Structure

The concept of a linear accelerator with spatially homogeneous strong focusing was originated in 1969 by two Russian scientists, I. M. Kapchinskii and V. A. Teplyakov.[1] The RFQ was first analyzed as a four-conductor line with quadrupolar symmetry as in Fig. 1. Two methods were suggested for driving the four conductor line with resonant cavities.[1,2]

Four-Chamber Resonator

The first was a four chamber resonator with cross sections as shown in Fig. 3. The cross sections that are shown correspond to planes that are $\beta\lambda/2$ apart longitudinally. The poles were cut off of as in electrostatic lenses to increase the potential difference between neighboring poles. Because the ideal pole tip is hyperbolic, cutting off the electrodes increased the non-linear field components. The TE210 mode has the desired quadrupole fields. Transverse electric fields are concentrated between electrodes near the beam centerline, whereas the magnetic flux runs the length of the cavity inside each chamber. The flux direction is opposite in adjacent chambers.

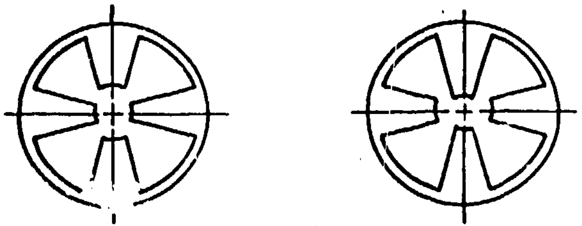

Fig. 3.
Cross sections of four chamber resonator.

Double H Cavity

The double H cavity in Fig. 4 was another approach to resonantly driving the four electrodes.[2,3] The pole tips are mounted on cylinders which have been split along two generatrices. The cylinders comprise the two H resonators and are similar in principle to two of the lobes in the four-chamber resonator.

Four-Vane Structure

The first structure tested at Los Alamos was a heavily loaded TE21 resonator. Two sets of internal structure were built; the double H resonator, Fig. 4, and the four vane, Fig. 5. The properties of the four

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vane were studied with a set of vanes having adjustable penetration. Testing of the double H structure was abandoned because of potential fabrication difficulties.

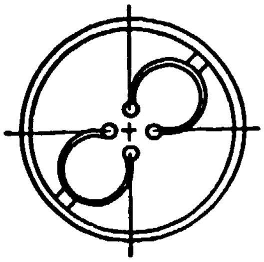

Fig. 4

Double H resonator.

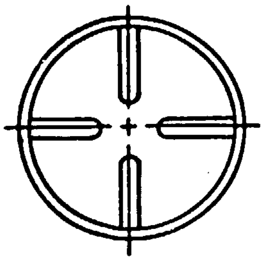

Fig. 5.

Four vane cavity.

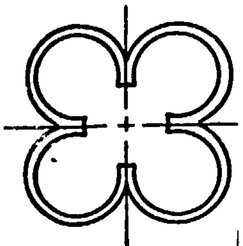

Fig. 6.

Cloverleaf cavity.

Cloverleaf Structure

The cloverleaf RFQ is basically a mechanical improvement over the four-vane design. Figure 6 illustrates the construction principle. Four pipes have flats ground ninety degrees apart on the outside wall. They are joined at these flats by welding and a hole is bored through their center. The bore leaves concave surfaces on the partitions between lobes and on these are mounted electrodes or vanes which are the pole tips. This design may be considered to have evolved two ways. First, it resembles a quadruple H-cavity, not far different from a double variety. It also resembles a four-vane cavity with the corners rounded for higher Q.

RF Properties of the Cavities

The RF properties of both the four-vane and the cloverleaf cavities have been investigated at low power.

Four-Vane Cavity

Vanes with exaggerated modulations were built to test the four-vane cavity. Longitudinal bead pulls with different sized needles proved conclusively that axial fields were present.

A second set of modulated vanes whose dimensions were a scaledown by five of the first modulated vanes was tested. The measured Z/Q was 1200 ohms/m. Interference from TE11 modes caused some noticeable field nonuniformity.

Since the TE210 mode has group velocity zero, its behavior in the cavity is similar to a non-post coupled Alvarez in that the mode is susceptible to geometrical tolerances. This became obvious with the scaled-down vanes because of the poor mechanical tolerances of the four-vane cavity. The solution was to design and build a more refined cavity with tighter construction tolerances. The result was the cloverleaf resonator diagrammed in Fig. 6.

Cloverleaf Structure

The first set of vanes tested in the new cavity were the scaled-down-by-five pole pieces modified for proper mounting. Although the axial fields were much flatter than in the four-vane structure, asymmetries were still present because of poor vane alignment resulting from the fabrication tolerances of the vanes.

Improved vanes closely approximating the theoretical ideal were tested. The vane shape is most accurately described as a sinusoidal hyperboloid. Bead pulls indicated flat axial fields with uniform and symmetric orientation even with little tuning. For an aperture 8.0 mm in diameter, the measured Z/Q was about 2400 ohms/m.

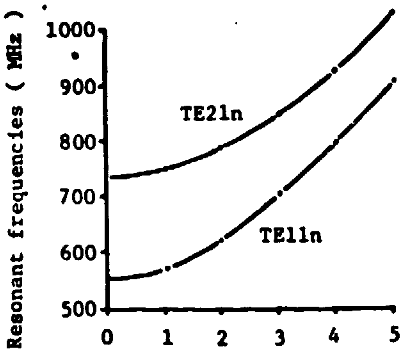

Fig. 7.

Dispersion curves for four vane.

Mode Interference

The dispersion curves for the TE11n and TE21n families of modes approach each other as the cavity loading is increased (i.e., as the RFQ aperture is decreased). For heavy loading, the TE110 mode may be closest to the desired TE210 mode. For other degrees of loading the nearest mode may be a TE11n mode with n > 0, depending on the length of the structure. These unwanted modes can distort the field distribution in two ways: one, by direct excitation from the response curve overlapping the drive frequency and, two, by mode mixing resulting from asymmetries in the cavity geometry. Mode interference has been observed experimentally as the failure of Ez to return to the baseline at every other minimum in the field distribution. Such a field distribution can destroy the ability of the RFQ to accelerate and bunch a beam.

Ideas for Improvement

Interstitial Vanes

Two measures may be taken to eliminate or reduce mode interference problems. If the offending mode is higher in frequency than the TE210 mode, the mode separation may be increased by adding interstitial vanes (Fig. 8) along the zero potential planes of the TE210 mode. These interstitial vanes are connected to the RFQ end walls and extend slightly into the region between the RFQ vanes. A more general solution is to avoid exciting any TE11n modes by driving the RFQ with judiciously arranged drives. Difficulties in achieving the required degree of symmetry with power splitters has led us to consider an external manifold structure which is resonantly coupled to the RFQ.

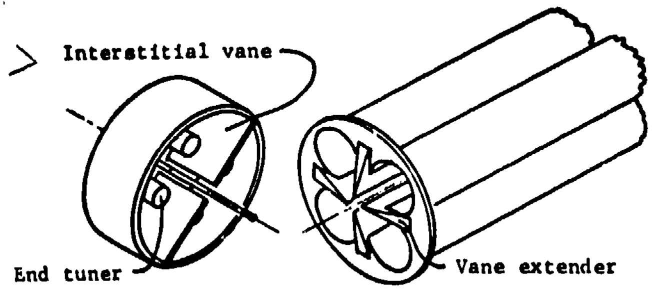

Fig. 8.

Cloverleaf RFQ with interstitial vanes, end tuners, and vane extenders.

End Tuners

Figure 8 shows the end tuners as adjustable slugs mounted in the endcap. The end loading may be varied to artificially create an open circuit at the cavity termination. The tuners may be adjusted to correct tilting and bowing of the Ez field distribution.

Vane Extenders

Rather than extend the end tuners into the cavity, it is possible to increase the length of the vanes nearly to the endwall if the base of the vanes is cut away as shown in Fig. 8. The wedge shape allows magnetic flux return for the TE21 modes and partially blocks that for the TE11 family.

If the vane extenders are properly made, the fields at the beam channel entrance and exit may be tailored to desired distributions. For the entrance, this may be a controlled field turn-on to achieve adiabatic capture. The exit will be configured to optimize beam injection into a drift tube linac.

Coax Manifold

For feeding RF power to the resonant cavity, symmetric drive is desirable. One power manifolding scheme employs a coaxial cavity with the RFQ as the center conductor. Resonant coupling loops transfer power from the region surrounding the center conductor to within each of the four lobes on the RFQ. This provides symmetric power drive to the cavity in several transverse planes along its length.

Coupled Circuit Analysis

Analysis of the stability of the field distribution of the RFQ with a resonantly coupled manifold is an interesting problem. If the longitudinal extent of the cavity is ignored, the RFQ with heavy loading may be modeled as a ring of four weakly-coupled resonators. The π mode of this ring corresponds to the desired TE210 mode. The two degenerate $\pi/2$ modes are analagous to the TE110 mode. The 0 mode can be related to the TE010 mode of the RFQ. In Fig. 9 the RFQ is represented by the outer ring of resonators. The central resonator represents the coaxial manifold and the four intermediate resonators are the coupling loops. Preliminary analysis of this model indicates that the 0 and $\pi/2$ azimuthal modes are suppressed and a family of three radial modes exists (the 0, $\pi/2$ and π modes). The desired operating mode is the azimuthal π mode, the radial $\pi/2$ mode and, if longitudinal extent is added, the longitudinal 0 mode. The coaxial manifold improves the balance and stability of the fields in the four RFQ lobes by providing an alternate path for azimuthal power flow with non-zero group velocity.

The properties of the transverse plane coupled oscillator model can be calculated by conventional equivalent circuit techniques with a 9 x 9 impedance matrix. Consideration of the longitudinal extent of the RFQ manifold combination requires a different approach. One of the authors (J. M. Potter) has developed a means of studying combinations of lumped circuit resonators and distributed transmission lines using chain matrix notation. This technique is particularly useful for studying RF power manifold systems. In the case of the RFQ manifold a ten-port chain matrix is required. This analysis is still under development.

Vane Design

One important facet of the RFQ design is the exact shaping of the vanes which define the beam channel. The correct vane shape is necessary to obtain the proper field distribution for accelerating with minimum beam losses. The shape is described by an equipotential surface in the electrostatic solution for the structure.

The fabrication technique for the vanes involves the cutting of blanks and then final shaping with a numerically-controlled (NC) mill. Figure 10 shows the final shape and the path the ball end cutter takes when the mill is run. Forty such passes per inch define the vane surface.

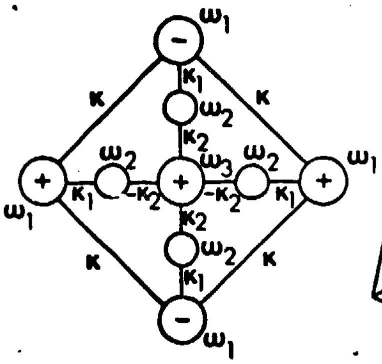

Fig. 9.

Coupled oscillator model for the transverse plane of the manifold coupled RFQ.

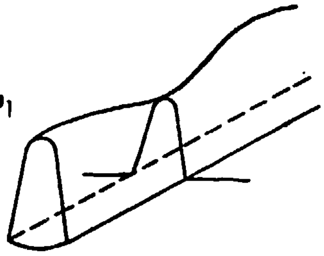

Fig. 10.

Cutter path for vane fabrication.

RFQ Applications

As a low energy accelerator, the RFQ has many appealing qualities. Its focusing period is half that of a drift tube system. Thus, the RFQ's transverse Coulomb limit is four times that of a drift tube linac.

The combination of low losses, high current limit, and low injection energy make the RFQ an ideal low energy end for a high intensity deuteron linac. The Fusion Materials Irradiation Test (FMIT) facility to be built at Richland, Washington, will use an RFQ at its injector end. It will be a deuteron linac for 35 MeV, 100 mA beam at 100% duty.

Acknowledgments

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