A SPIRAL-RESONATOR RADIO-FREQUENCY QUADRUPOLE ACCELERATOR STRUCTURE*

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Summary

A radio-frequency quadrupole (RFQ) structure operating at low frequency has been developed for possible use in accelerators for heavy ion fusion or Tokamak plasma heating. The structure uses a series of shunt spiral inductors placed periodically along the electrodes of an electric quadrupole to achieve resonance at the desired frequency. A 1.2-m-long model has been constructed for low-power testing. The model resonates near 12 MHz and has radial dimensions that are reduced by a factor of 15 compared to the commonly used four-vane resonator.

Introduction

The increasing number of applications for high-current linear accelerators emphasizes the importance of the RFQ accelerating structure. The RFQ can accept a high-current dc beam from an ion source and focus, bunch, and accelerate the ions to several MeV/nucleon. For operation with very high-current beams, often the RFQ must be designed to operate with such a low frequency that the resonator's transverse dimensions become unacceptably large. In this report we describe recent tests of a spiral resonator designed to provide low-frequency excitation to the four poles of an RFQ. The spiral resonator allows a substantial decrease in transverse dimensions compared to four-vane configurations that are commonly used. Before the RFQ was developed, spiral resonators were constructed at Los Alamos, Frankfurt, and Heidelberg for use in conventional accelerator systems. At Frankfurt, the spiral and other alternative methods of exciting RFQ poles have been investigated.[1]

RFQ accelerator techniques using frequencies from 80 to 450 MHz now are being applied in many projects. These include projects at Berkeley, Brookhaven, Chalk River, Darmstadt, Frankfurt, Julich, Los Alamos, Moscow, Saclay, Serpukhov, and Tokyo. In addition to these ongoing projects, there are possible applications of RFQ accelerators operating with lower frequencies. These projects are listed below.

- Heavy Ion Fusion
- Tokamak Plasma Heating
- Tritium and Fissile Material Production
- Directed-Energy Beam Research
- Advanced Research Accelerators

Some of these applications may require the use of frequencies as low as 6 MHz, where the four-vane resonator would have an ∿12-m diameter. For RFQ frequencies below ∿25 MHz, a marked reduction in resonator size must be obtained to reduce cost and to facilitate engineering design.

Requirements for high radial-brightness beams may limit the extent to which low frequencies can be applied. Different applications have greatly varying brightness requirements, some of which can be met through use of funneling techniques discussed later.

High-Current RFQ Beam-Dynamics Requirements

Analytical formulas have been developed to predict the beam-current capability of linear accelerator systems. For the RFQ, these predictions have been confirmed in the proof-of-principle experiment at Los Alamos in 1980. The transverse current capacity is proportional to the wavelength squared, to the charge-to-mass ratio of the ion, and to the ion velocity. Thus, low frequencies are especially important to the production of high-current beams of low-velocity heavy ions.

The use of low-frequency RFQs is compatible with the method proposed to combine two bunched beams by funneling. In this scheme, two beams are combined by using a pulsed deflector to produce a single collinear beam with interlaced microstructure pulses. This beam then is further accelerated in a linac operating with twice the frequency. Multiple funneling stages and linacs of increasing frequency will progressively increase the beam's radial brightness. This means that starting with low frequency does not commit the whole linac system to low-frequency operation. It also means that the lowest velocity structure, the RFQ, is at the lowest frequency, and thus the RFQ resonator size is a predominant consideration. The spiral resonator RFQ system discussed in this paper is suitable for operation with a single beam or with an array having multiple beams that can be combined by the funneling technique. Table I gives two examples of heavy ion RFQs. Both were designed to operate at low frequency to allow high-current beams to be accelerated.

TABLE I

LOW FREQUENCY RFQ DESIGNS

	Heavy Ion Fusion[a]	Plasma Heating
Frequency (MHz)	12.5	5.9
Ion	Xe^{+1}	O^{+1}
Input energy (MeV)	0.30	0.40
Output energy (MeV)	10.0	16.0
Input beam current (mA)	50	1500
Transmission efficiency (%)	93	91
Length (m)	28	22

[a]This design is described in Ref. 2.

RFQ Spiral Resonator - Mechanical Design

The main objective was to test a spiral resonator RFQ structure at low power to determine its rf characteristics. In addition, we wanted to solve some of the design problems that would be important to future high power applications. An existing copper-plated tank, 1.2 m long with 0.40 m i.d., was chosen to contain the spirals. Because only the rf properties were to be tested, the four RFQ poles were made from 1.91-cm-diam straight copper tubes 1.08 m long. Opposite poles were separated by 1.91 cm. The four poles were supported by four Archimedean spirals as shown in Fig. 1. At the center, each spiral was electrically connected to a diagonal pair of poles. Macor insulators were used to mechanically support the other pair of poles. Adjacent spirals were counterwound and were electrically connected to alternate pairs of RFQ poles. The two types of spirals and their connections to the RFQ poles are shown in Fig. 2. Although in each spiral plane all four poles were mechanically

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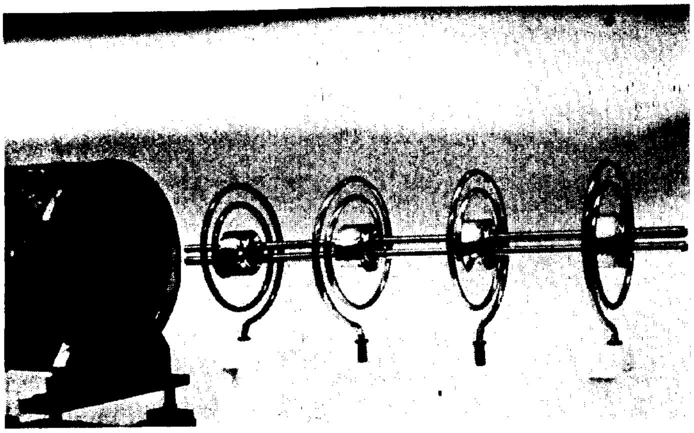

Fig. 1. The four-spiral assembly ready to be placed in the tank.

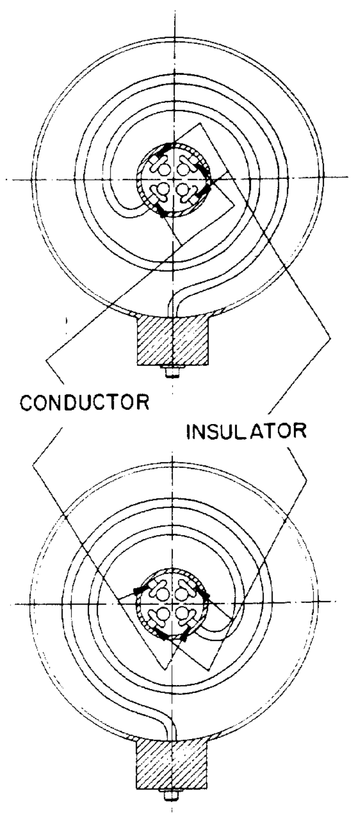

Fig. 2.
The two types of spirals showing their connections to the RFQ poles.

supported, if desired the insulators can be completely removed and each pole then would be mechanically supported at every other spiral.

The spirals were constructed from 1.27-cm-diam stainless steel tubing with a 0.165-cm wall thickness. A steel mandrel mounted in a lathe chuck was used to wind the spirals. After winding and before removal from the mandrel, the spirals were heat treated to remove stresses. Electrical contact with the outer cylinder was made with a compression fitting and a copper gasket. In future designs requiring cooling water, the flow can be inward to the center of a spiral, then along channels inside two poles, and finally can return outward through the second adjacent spirals.

Mechanical stiffness in the transverse direction was high, but longitudinally the structure was somewhat flexible. A longer structure with more spirals would increase the longitudinal stiffness, or it could be increased by the use of spirals of rectangular cross section. Proof of sufficient mechanical rigidity must await construction and test of a spiral resonator at full rf power.

Spiral Resonator Shunt Impedance and Focusing Impedance

For RFQ structures, a convenient definition of shunt impedance is

$$Z_s = \frac{V^2}{P/\ell} ,$$

where V is the vane-to-vane potential difference and P/ℓ is the power per unit length required to achieve the potential difference V. In terms of measurable properties, the shunt impedance can be shown to be approximately

$$Z_s = \frac{Q}{\pi f \; C/\ell} ,$$

where Q is the cavity quality factor, f is the operating frequency, and C/ℓ is the effective capacitance per unit length. For low-frequency structures such as the spiral resonator RFQ, the effective capacitance C can be measured by observing the frequency change Δf caused by adding an increment of capacitance ΔC across the vane tips. Because $2(\Delta f/f) = -\Delta C/C$, we find that $C = 0.5(\Delta Cf/\Delta f)$.

For the spiral resonator we determined that C = 194 pF. This value is somewhat higher than expected. Further investigation showed that 51 pF of this capacitance results from the high dielectric-constant insulators used in the structure. Reducing the dielectric constant to 2 would reduce the capacitance contribution from the insulators to ~5 pF, for a net capacitance of ~148 pf.

The Q of the structure is 600, the length is 1.08 m, and the frequency is 11.7 MHz. These parameters yield a shunt impedance Z_s of 91 kΩ · m with the ceramic insulators and 119 kΩ · m with better insulators. Note that unlike the usual situation with linear accelerators, the shunt impedance varies inversely with the length. This occurs because the voltage is transverse to the direction in which the length is increased. The power required for V = 100 kV is 84 kW/m with the lower dielectric constant insulators.

The focusing impedance has been defined as

$$Z_f = \frac{(dE/dx)^2}{P/\ell} ,$$

where dE/dx is the quadrupole strength on the axis. The focusing impedance can be related to the shunt impedance by the approximation

$$Z_f = \frac{Z_s}{r_o^4} ,$$

where r_o^4 is the RFQ radius parameter. Focusing impedance for the spiral resonator RFQ is 1.5×10^{13} Ω/m^3 for the lower dielectric constant insulators.

Figure 3a is a plot of the perturbation caused by pulling a 0.125-in.-diam brass bead transversely across the axis and between the rods. The square root of the perturbation data is plotted in Fig. 3b, taking into account the phase reversal across the axis. From the slope of the curve at the axis crossing, one can

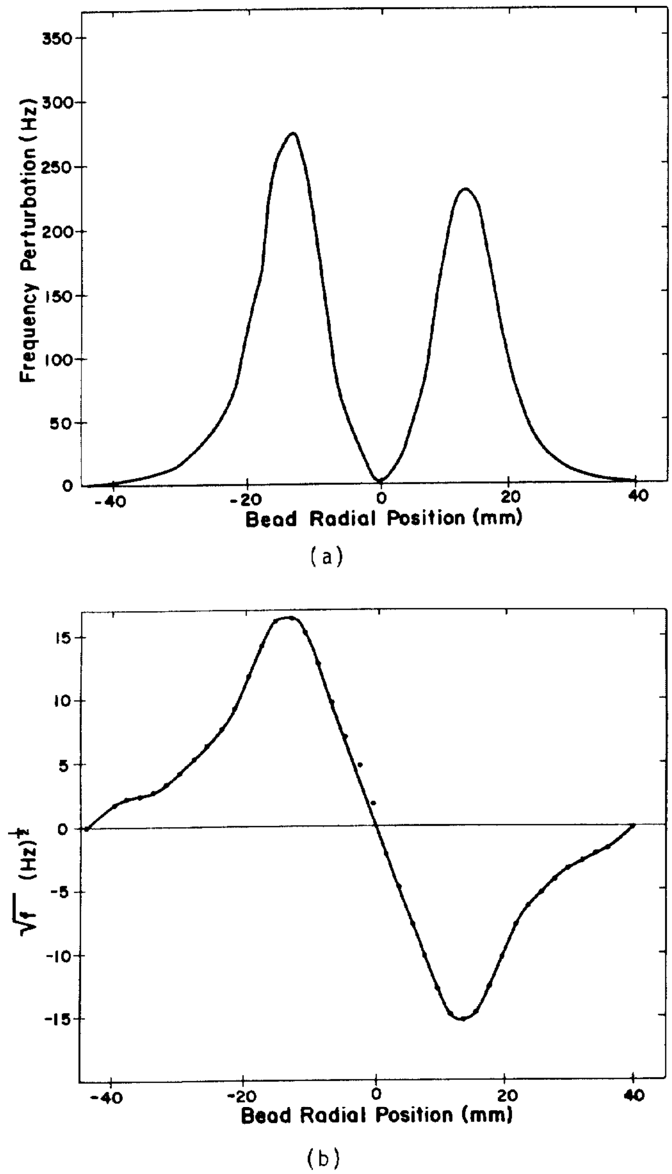

Fig. 3. (a) Perturbation data from a transverse bead pull; (b) electric field strength from the perturbation measurement.

determine the focusing impedance using the Slater perturbation theorem. The results of this measurement do not agree with the simple ΔC measurement discussed above; we have not yet determined the cause of this discrepancy.

The lower frequency modes of the spiral resonator are widely spaced. The mode of interest at 11.7 MHz has the lowest frequency, and it can be called the + - + - mode, where at a certain time this designates the polarities of the centers of the four spirals. The next higher mode has been identified as the + + + + mode with a 33-MHz frequency. It has a much higher frequency because of two effects. First, because all the RFQ poles have the same voltage and polarity, they present no capacity load to the spirals; furthermore, at a given time, the + + + + mode has spiral currents that all flow either inward or outward. Because every other spiral is counterwound, the mutual inductive coupling between spirals is reduced, and this also raises the resonant frequency.

Acknowledgments

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References

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