LA-UR-80-1855

MASTER

TITLE: THE RADIO-FREQUENCY QUADRUPOLE: GENERAL PROPERTIES AND SPECIFIC APPLICATIONS

AUTHOR(S): R. H. Stokes, K. R. Crandall, R. W. Hamm, F. J. Humphry, R. A. Jameson, L. A. Knapp, J. M. Potter, G. W. Rodenz, J. E. Stovall, D. A. Swenson, and T. P. Wangler

SUBMITTED TO: XIth International Conference on High Energy Accelerators, CERN, Geneva, July 7-11, 1980

University of California

LOS ALAMOS SCIENTIFIC LABORATORY
Post Office Box 1663 Los Alamos, New Mexico 87545
An Affirmative Action/Equal Opportunity Employer

Form No. 836 R3
St. No. 2629
12/78

UNITED STATES
DEPARTMENT OF ENERGY

THE RADIO-FREQUENCY QUADRUPOLE: GENERAL PROPERTIES AND SPECIFIC APPLICATIONS*

R. H. Stokes, K. R. Crandall, R. W. Hamm, F. J. Humphry, R. A. Jameson, E. A. Knapp,
J. M. Potter, G. W. Rodenz, J. E. Stovall, D. A. Swenson, and T. P. Wangler
Los Alamos Scientific Laboratory, Los Alamos, NM 87545 USA.

ABSTRACT

The radio-frequency quadrupole (RFQ) linac structure is being developed for the acceleration of low-velocity ions. Recent experimental tests have confirmed its expected performance and have led to an increased interest in a wide range of possible applications. We review the general properties of RFQ accelerators and present beam dynamics simulation results for their use in a variety of accelerating systems. These include the low-beta sections of the Fusion Materials Irradiation Test Accelerator, a 200-MHz proton linear accelerator, and a xenon accelerator for heavy ion fusion.

1. INTRODUCTION

Two years ago the Los Alamos Accelerator Technology Division initiated a program to investigate the properties of the radio-frequency quadrupole (RFQ) accelerating structure. The RFQ is a new concept originally proposed by Kapchinskii and Teplyakov.[1] Our development of this structure, the first outside of the USSR, has culminated in a successful experimental test[2] of the RFQ principle. We conclude that the RFQ offers an attractive solution to the low-velocity problems that are an intrinsic part of many accelerator systems.[3] In this paper we will emphasize the RFQ's functional properties and briefly discuss our methods for designing RFQ systems. Finally, we will describe three applications where an RFQ has been designed to solve the low-velocity problems in widely diverse accelerator systems.

The RFQ uses rf transverse electric fields to focus ions traveling along its axial region. Figure 1 is a schematic section of the RFQ resonator. It operates in a modified TE_{210} mode in which the currents flow transversely to the z-axis. The current flow results in + - + - polarities on the pole tips at a certain time, thus producing a quadrupole focusing, or defocusing, force in a given transverse plane. One-half cycle later these forces reverse sign to produce an overall strong focusing effect. The focusing force at a given time is spatially continuous along the z-axis. If the pole tips have a constant

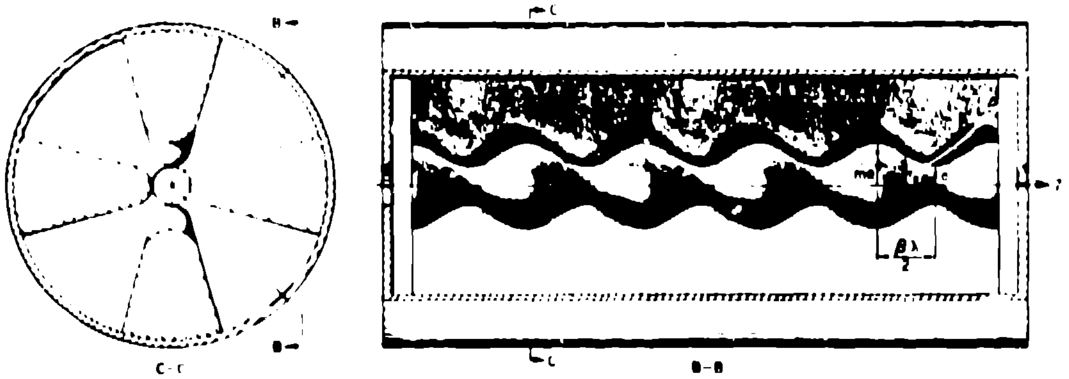


Fig. 1. Schematic Drawing of an RFQ Resonator.

---

*Work performed under the auspices of the US Department of Energy, Office of Energy Research, Office of Fusion Energy, and the US Department of Health, Education, and Welfare, National Cancer Institute.

radius, only a radial focusing force is present. In Fig. 1 the pole tips have a sinusoidal-like variation in radius. Between the x-plane and y-plane pole tips this variation in radius is shifted by $\beta\lambda/2$. This pole-tip modulation produces longitudinal accelerating fields in addition to the transverse focusing field.

The operation of an RFQ system in the USSR has been described previously.[4] Early in 1980 a highly successful experimental test at Los Alamos confirmed predicted behavior and general capabilities of an RFQ system.

2. GENERAL PROPERTIES OF THE RFQ

An RFQ system can be designed to accept an intense low-velocity unbunched ion beam from a low-voltage dc injector; then it will provide radial focusing, bunching, and acceleration to a velocity where a conventional linac operates efficiently. Because the electric force is independent of velocity, the RFQ is especially effective in the radial focusing of low-velocity ions. In typical systems that we have designed, the dc injector can have a voltage of 50 kV for protons or 250 kV for Xe^{+1} ions. Having contained the beam radially, the RFQ then can provide useful longitudinal functions. For example, it can bunch the beam slowly enough to capture a very high percentage of the injected beam. This adiabatic bunching can be accomplished in a reasonable distance because of the low velocity of the ions. The bunching cycle also can be designed to increase the current capacity of the system. While the beam is being bunched, it is also being accelerated, so that by the time the final synchronous phase is reached, the beam energy has been increased by about a factor of ten. This allows acceptance of high-current beams at the input, and acceleration with only minimal emittance growth. In applying the RFQ in a specific case, it is possible to optimize its characteristics in a flexible way to obtain the desired compromise between transmission efficiency, emittance growth, beam current capacity, overall length, and power dissipation.

Techniques to provide rf power to RFQ systems have been described by Potter, et al.[5] A 4-vane resonator similar to Fig. 1 can be used for frequencies greater than about 50 MHz, where the outer diameter is about 1.2 m. With lower frequencies, a Wideroe resonant system could be used; or with very low frequencies suitable for heavy ions, an externally resonant structure[6] may become useful.

3. BEAM DYNAMICS ANALYSIS AND POLE-TIP DESIGN

As a basis for beam dynamics simulation calculations and for construction of RFQ pole tips we use the lowest order potential function. Figure 2 summarizes our procedure. Electric fields obtained from the potential function were used to construct transformations for the beam dynamics simulation program PARMTEQ.[7,8] This program, which includes space charge effects, analyzes specific RFQ designs to obtain transmission efficiency, radial emittance growth, and radial and longitudinal characteristics of the output beam. From an appropriate isopotential surface, we obtain the radial variation of the pole tips and the variation of their radius of curvature in the transverse plane, both as a function of z. Figure 1 shows the unit cell of length $\beta\lambda/2$, through which the radius varies from ma to a. In the center of the unit cell, the pole tips have quadrupolar symmetry and the radius r_0. The pole tips are constructed by generating a data file on magnetic tape that is used as input to a numerically controlled milling machine.

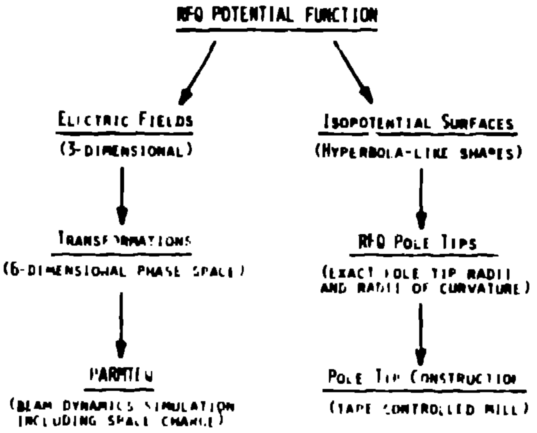


Fig. 2. Beam Dynamics Simulation and Pole Tip Geometry.

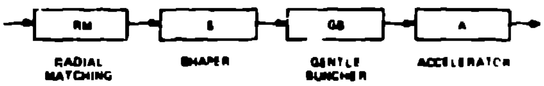


Fig. 3. RFQ Functional Block Diagram.

4. BEAM DYNAMICS DESIGN PROCEDURES FOR RFQ SYSTEMS

The methods used to synthesize RFQ systems to meet specific objectives have been previously described.[8] Figure 3 shows how the design procedures can be divided into four separate sections. The unbunched beam from the dc injector first goes into the radial matching section, where the radial focusing strength is increased from a low initial value to a higher final value in $\sim 5\beta\lambda$. This allows the beam to adapt itself adiabatically to the time-varying focusing forces. The next section is the shaper where we start to ramp both ϕ_s and E_0, the average longitudinal field. The phase angle ϕ_s start at -90° and increases linearly with z. E_0 starts at zero and is slowly turned on by increasing the amplitude of the pole-tip modulation. If the parameters are chosen correctly, we can "shape" the particle distribution at the output of the shaper to occupy the desired level in the phase stable region of the bucket. Next is the gentle buncher where two conditions are imposed, as suggested by Kapchinskii. The average z-length of the bunch is held constant and the small amplitude longitudinal frequency is held at a fixed value. This allows the final value of ϕ_s to be attained at the end of the gentle buncher and preserves the particle distribution throughout. In the accelerator section, the ions are accelerated to their final energy at a constant value of ϕ_s.

The design methods described previously[8] were constrained to make the average radius of the pole tips r_0 constant, except in the radial matching section. This kept the distributed capacitance nearly constant for easier resonator tuning. Also, the quantity V/r_0 is held constant, where V is the intervane voltage, allowing control of the peak surface field, which occurs near the point where the poles have minimum separation. These constraints are consistent with a constant voltage along the vanes and with a constant value of the focusing strength B. After experience in tuning RFQ resonators, we believe we can achieve specified voltage distributions that vary with z within certain limits; therefore, we have developed a new design procedure that holds the bore radius, a, at the same constant value in both the shaper and gentle buncher. This constant-a method is illustrated in the FMIT RFQ design to be discussed later. One advantage of the constant-a design is that the rf power required to excite the constant-a RFQ is less than with the constant-r_0 design. We have compared the FMIT RFQ with an equivalent constant-r_0 design of the same length and the same current capacity. The structure power required for the shaper, plus gentle buncher sections of the constant-a RFQ, was 50% of that required by the constant-r_0 design.

5. PROPERTIES OF THE RFQ FOUR-VANE RESONATOR

The RFQ resonator can be understood in terms of the modes of a waveguide with uniform four-fold symmetrical cross section. The vane-tip potentials are assumed to be constant, independent of the z-coordinate. For heavy capacitive loading by the vanes, two families of modes are necessary for a reasonable approximation of the field distribution, the TE_{21n} and the TE_{11n} modes. The TE_{lmn} designation refers to the RFQ modes analogous to the modes of a right circular cylinder. The mode with uniform vane potentials and quadrupolar fields is the TE_{210}, which is the RFQ operating mode.

The TE_{110} modes are a degenerate pair of modes with dipole-like fields. The effect of these modes is to unbalance the azimuthal field distribution, resulting in different vane-tip potentials for each vane. Longitudinal field errors arise from mixing in TE_{21n} modes with $n > 0$, resulting in vane-tip potentials that vary with z. Contributions from the TE_{11n} modes with $n > 0$ affect both the azimuthal and longitudinal field distributions. The modes that are most easily mixed by structure tuning errors are those lying closest to the TE_{210} mode. Accidental degeneracies are a serious problem. For example, for a given loading there is a length for which the frequencies of the TE_{210} and TE_{111} modes are identical.

The RFQ operating mode can exist only for an open circuit boundary condition. This boundary condition is simulated by the use of four end tuners that are capacitively coupled to the ends of the vanes. Their capacity, resonating in parallel with the inductance of the end caps, provides a high impedance termination.

In a structure with a small aperture and a strongly radially dependent field, traditional bead-pull techniques are difficult to use. To tune the experimental test model RFQ, we measured the relative magnetic fields at the resonator outer wall by observing the frequency change caused by a metal plunger inserted at various positions along the structure. A uniform and symmetrical magnetic field corresponds to the desired vane tip potential distribution, if there are no large geometrical errors in the vane gap dimensions. The test model RFQ was sufficiently short so that it was possible to adjust the average azimuthal field distribution by tuning each quadrant, and to adjust the longitudinal potential distribution using the end tuners.

To couple power into the RFQ without disturbing the field distribution, a coaxial manifold is used.^{5} The manifold is a TEM mode resonator with 45^{0} angled coupling slots into each rf quadrant at each manifold magnetic field maximum. The combined system is operated in the zero mode and tuned for minimum slot excitation.

6. RADIO-FREQUENCY QUADRUPOLE EXPERIMENTAL TEST

Beginning in February 1980, we conducted a full-scale experimental test of the RFQ principle. The test linac was designed to accept protons from a 100-kV dc injector and to focus, bunch, and accelerate to a final energy of 640 keV. The RFQ test resonator had 1.1-m-long vanes and a 0.15-m o.d. Radio-frequency power was furnished by a 425-MHz klystron that was coupled to the resonator through a coaxial manifold and coupling slots. The beam dynamics design for this test and the calculated performance have been described previously.^{8}

The momentum spectrum of the accelerated beam was measured with a 45^{0} magnetic analyzing system. This system confirmed an expected 640-keV energy for the accelerated particles and we observed no low-energy components. Adjusting the RFQ vane voltage made it possible to rotate the final longitudinal phase space to yield a minimum energy spread of 3% FWHM.

The transmission efficiency was measured with biased Faraday cups immediately before and after the linac. With a 30-mA injected beam, the output beam current was 26 mA, corresponding to the predicted 87% transmission efficiency.

The input beam emittance was measured ahead of the lens that matches the beam from the dc injector into the RFQ, and the output emittance was measured immediately following the RFQ tank. Typical measurements for a 25-mA output beam indicate a normalized rms emittance growth factor of ~ 1.5. We believe this to be an upper limit, because the injected beam's emittance is somewhat increased in the matching lens.

The reliability and the simplicity of operation of the test linac were outstanding. After an initial conditioning period, the RFQ operated continuously, accelerating a 20-mA beam current for more than a month at a duty factor of 0.1%. Also, the test has shown that the RFQ is tolerant of both constructional errors and errors in the rf resonator tuning.

7. APPLICATIONS OF THE RFQ

The great flexibility inherent in the RFQ concept suggests its use in a wide variety of accelerator systems. Recently we have made preliminary beam dynamics designs for a large number of cases where the requirements were widely different. We will illustrate these by describing three systems. Each example will be discussed briefly, and most of the details will be presented in tabular form.

7.1 FMIT RFQ

The first example is the Fusion Materials Irradiation Test (FMIT) accelerator being designed by Los Alamos for the Hanford Laboratory. The deuteron beam from this accelerator will bombard a lithium target to produce neutrons to test materials for fusion reactors. The final deuteron energy is 35 MeV, and the output current is 100 mA, with 100% macroscopic duty factor. The RFQ will be used in the energy range 0.1 - 2.0 MeV, after which a drift-tube linac will be used for acceleration to the final energy. Table 1 summarizes the preliminary design parameters and principal results. The current limit was calculated from the formulas given by Wangler.[9] The emittances are normalized values and are to be multiplied by π to obtain the ellipse area in cm·mrad units. The quantity F

Table 1

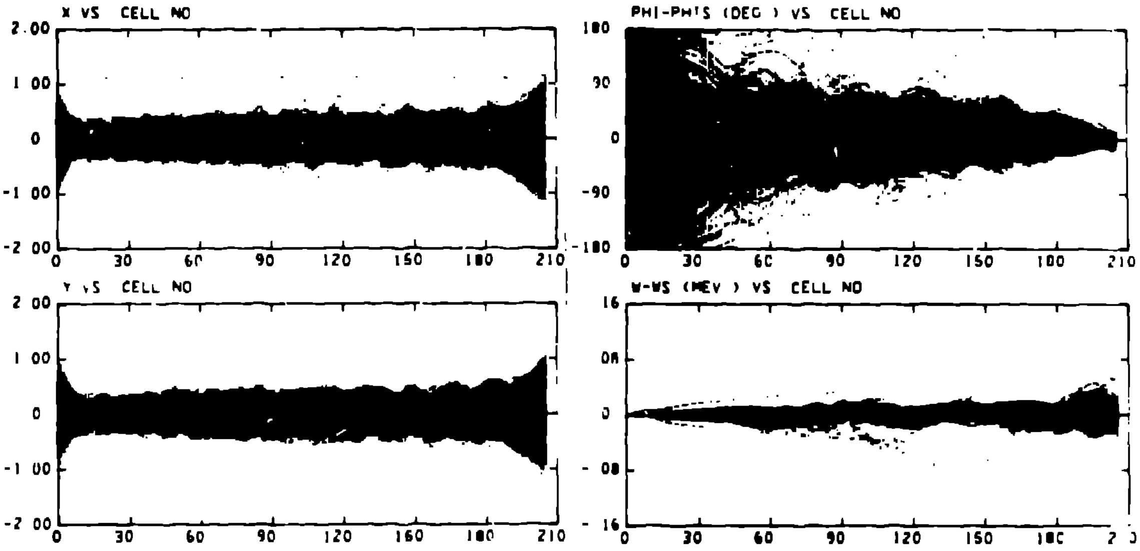
FMIT RFQ

Ion: Deuteron
Frequency: 80 MHz
Design Type: Constant-a
Nominal Current: 100 mA
Current Limit: 192 mA

PARMTEQ Results
Input Current: 100 mA
Output Current: 98 mA

Emittance
Input (90%): 0.070
Output (90%): 0.194
Input (RMS): 0.017
Output (RMS): 0.045

	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
W(MeV)	0.10	0.10	0.11	1.13	2.00
F	0.24	1.50	1.50	1.50	1.50
m	1.00	1.00	1.09	2.07	1.80
a(cm)	6.93	1.11	1.11	1.11	1.72
r_0(cm)	6.93	1.11	1.16	1.74	2.41
ϕ_s(deg)		-90	-83	-30	-30
E_0(MV/m)	0	0	0.27	1.72	1.50
V(kV)	129	129	134	202	282
B	0.2	7.82	7.51	4.99	3.57
L(m)	0	0.2	1.6	5.0	5.9



(a) Fig. 4. PARMTEQ Simulation Results. (b)

is the factor by which the Kilpatrick limit is multiplied to obtain the peak surface field on the pole tips; L is the cumulative RFQ length from the input. For the operating frequency of 80 MHz, the 4-vane-type resonator has ~ 0.8-m o.d. Figure 4 shows the results of analyzing this RFQ with PARMTEQ; beam characteristics are plotted versus cell number. In Fig. 4(a), the x- and y-projections of 360 particles are plotted at the point in each cell where the beam is circular. The upper and lower dotted lines give the bore dimensions. The top of Fig. 4(b) shows the bunching of 360 particles initially distributed uniformly in phase (unbunched). The ordinate is the particle phase minus the synchronous phase. At the bottom, the particle energy minus the synchronous energy is plotted. In the phase and energy plots, the dotted lines give the location of the zero space-charge separatrix.

7.2 200-MHz Proton Linac RFQ

Many high- or medium-energy facilities have a low-energy accelerator system consisting of a 750-kV Cockcroft-Walton generator plus a 200-MHz drift-tube linac. The next example illustrates how an RFQ could perform these functions up to a 2-MeV energy. We have chosen to use a dc injector operating with a 50-keV potential. Table 2 gives the results.

Table 2

200-MHz Proton Linac RFQ

Particle: Proton
Frequency: 200 MHz
Design Type: Constant-r_0
Nominal Current: 40 mA
Current Limit: 87 mA

PARMTEQ Results
Input Current: 42 mA
Output Current: 41 mA

Emittance
Input (90%): 0.042
Output (90%): 0.055
Input (RMS): 0.010
Output (RMS): 0.013

W(MeV)	0.05	0.05	0.06	0.58	2.00
F	0.26	1.50	1.50	1.50	1.50
m	1.00	1.00	1.08	2.40	2.40
a(cm)	3.12	0.54	0.52	0.30	0.30
r_0(cm)	3.12	0.54	0.54	0.54	0.54
ϕ_s(deg)	–	-90	-83	-30	-30
E_0(MV/m)	0	0	0.34	2.16	1.20
V(kV)	85	85	85	85	85
B	0.21	7.00	7.00	7.00	7.00
L(cm)	0	8	53	188	328

7.3 Heavy Ion Fusion RFQ

Recently, proposals to investigate the feasibility of heavy-ion induced fusion for commercial power production have generated interest in large linear accelerator systems. The low-beta part of these systems tends to be one of the serious overall limitations. The RFQ, which can be constructed in a special manner for low frequencies, appears to offer an attractive solution to this low-beta problem. The following example is a system[10] to accelerate Xe^{+1} ions from 0.24 to 5.0 MeV. Table 3 gives the results.

Table 3

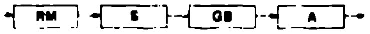
Heavy Ion Fusion RFQ

Particle: Xe^{+1}
Frequency: 12.5 MHz
Design Type: Constant-r_o
Nominal Current: 25 mA
Current Limit: 42 mA

PARMTEQ RESULTS

Input Current: 30 mA
Output Current: 29 mA

Emittance
Input (90%): 0.007
Output (90%): 0.031
Input (RMS): 0.0017
Output (RMS): 0.0068



W(MeV)	0.24	0.24	0.25	2.50	5.00
F	0.28	1.60	1.60	1.60	1.60
m	1.00	1.00	1.05	1.48	1.48
a(cm)	10.5	1.81	1.77	1.45	1.44
r_o(cm)	10.5	1.81	1.81	1.81	1.81
ϕ_s(deg)	—	-90	-86	-32	-32
E_o(MV/m)	0	0	0.15	0.85	0.65
V(kV)	200	200	200	200	200
B	0.09	2.85	2.85	2.85	2.85
L(m)	0	0.2	3.4	21.9	27.0

* * *

REFERENCES

1) I. M. Kapchinskii and V. A. Teplyakov, Prib. Tekh. Eksp., No. 2, 19 (1970).

2) R. W. Hamm, K. R. Crandall, L. D. Hansborough, J. M. Potter, G. W. Rodenz, R. H. Stokes, J. E. Stovall, D. A. Swenson, T. P. Wangler, C. W. Fuller, M. D. Machalek, R. A. Jameson, E. A. Knapp, and S. W. Williams, Proc. Int. Conf. on Low Energy Ion Beams 2, Univ. of Bath (April 1980).

3) D. A. Swenson, Proc. 1979 Linear Accelerator Conf., Montauk, NY (Sept. 1979).

4) B. M. Gorshkov, S. A. Il'evskii, G. M. Kolomenskii, S. P. Kuznetsov, N. N. Kutorga, A. P. Mal'tsev, K. G. Mirzoev, V. B. Stepanov, V. A. Teplyakov, and, I. M. Shalashov, Sov. Phys. Tech. Phys. 22 (11) (Nov. 1977).

5) J. M. Potter, S. W. Williams, F. J. Humphry, and G. W. Rodenz, IEEE Trans. NS-26, 3745 (1979); J. M. Potter, Proc. 1979 Linear Accelerator Conf., Montauk, NY (Sept. 1979).

6) D. A. Swenson, Proc. Heavy Ion Fusion Accelerator Study, Berkeley, CA (Oct.-Nov. 1979).

7) R. H. Stokes, K. R. Crandall, J. E. Stovall, and D. A. Swenson, IEEE Trans. NS-26, 3469 (1979).

8) K. R. Crandall, R. H. Stokes, and T. P. Wangler, Proc. 1979 Linear Accelerator Conf., Montauk, NY (Sept. 1979).

9) T. P. Wangler, Los Alamos Report LA 8388 (May 1980).

10) T. P. Wangler and R. H. Stokes, Proc. Heavy Ion Fusion Accelerator Study, Berkeley, CA (Oct.-Nov. 1979).