IEEE Transactions on Nuclear Science, Vol. NS-28, No. 3, June 1981

THE RADIO-FREQUENCY QUADRUPOLE - A NEW LINEAR ACCELERATOR*

R. H. Stokes, T. P. Wangler, and K. R. Crandall
Los Alamos National Laboratory, Los Alamos, NM 87545

Summary

In many Laboratories, great emphasis now is placed on the development of linear accelerators with very large ion currents. To achieve this goal, a primary concern must be the low-velocity part of the accelerator, where the current limit is determined and where most of the emittance growth occurs. The use of magnetic focusing, the conflicting requirements in the choice of linac frequency, and the limitations of high-voltage dc injectors, have tended to produce low-velocity designs that limit overall performance. The radio-frequency quadrupole (RFQ) linear accelerator, invented in the Soviet Union and developed at Los Alamos, offers an attractive solution to many of these low-velocity problems. In the RFQ, the use of RF electric fields for radial focusing, combined with special programming of the bunching, allows high-current dc beams to be captured and accelerated with only small beam loss and low radial emittance growth. Advantages of the RFQ linac include a low injection energy (20-50 keV for protons) and a final energy high enough so the beam can be further accelerated with high efficiency in a Wideröe or Alvarez linac. These properties have been confirmed at Los Alamos in a highly successful experimental test performed during the past year. The success of this test and the advances in RFQ design procedures have led to the adoption of this linac for a wide range of applications. The beam-dynamics parameters of three RFQ systems are described. These are the final design for the prototype test of the Fusion Materials Irradiation Test (FMIT) accelerator, the final design for the prototype test of the Pion Generator for Medical Irradiations (PIGMI), and an improved low-velocity linac for heavy ion fusion.

*Work performed under the auspices of the US Department of Energy.

Introduction

In the development of high-current ion linacs there has been a continuing challenge in the low-velocity accelerator that follows the ion source. In 1978 the Los Alamos Accelerator Technology Division initiated a program to develop improved low-velocity systems. The program was based on the RFQ linear accelerator that had been suggested by Kapchinskii and Teplyakov[1] in 1970. Our development of this linac,[2-7] the first outside the USSR, culminated in a highly successful experimental test[8] that began in February 1980. This test not only confirmed the attractive general properties of an RFQ linac, but also verified our approaches to beam dynamics and resonator design. Our previous papers[2-8] have discussed this experimental test, the RFQ four-vane resonator, beam-dynamics methods, and specific RFQ linacs. In this paper, we review RFQ characteristics, discuss the increasing interest in its application, and present three new RFQ beam-dynamics designs.

Figure 1 is a schematic drawing of an RFQ accelerator. It shows the interior 4-vane resonator and the exterior coaxial manifold used to couple RF power into the resonator through angled coupling slots.

General Properties of the RFQ

The RFQ uses RF transverse electric fields to focus ions traveling along its axial region. Figure 2 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

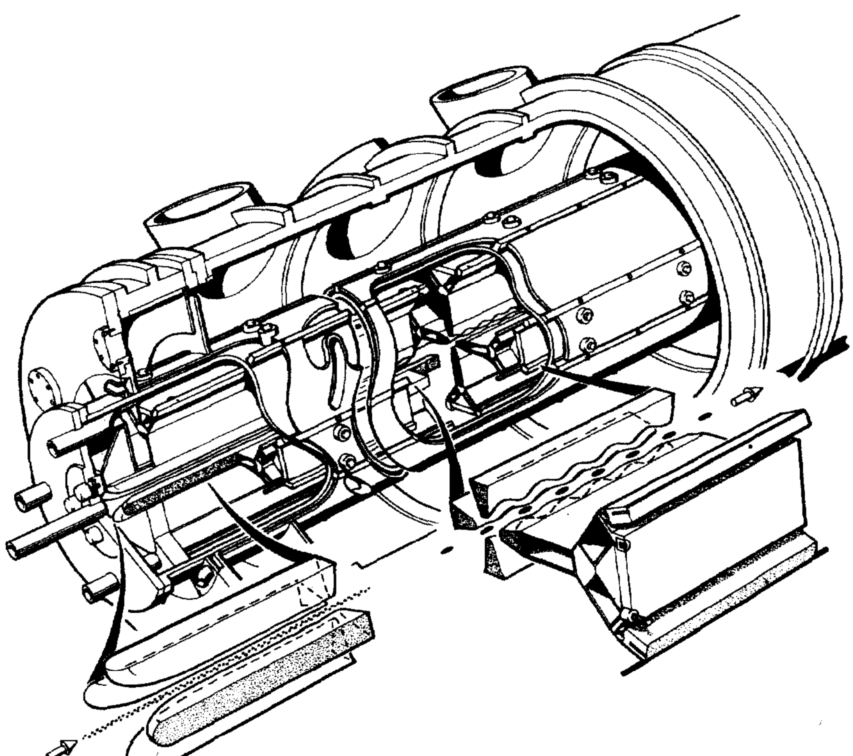

Fig. 1. Drawing of an RFQ with manifold.

0018-9499/81/0600-1999$00.75©1981 IEEE

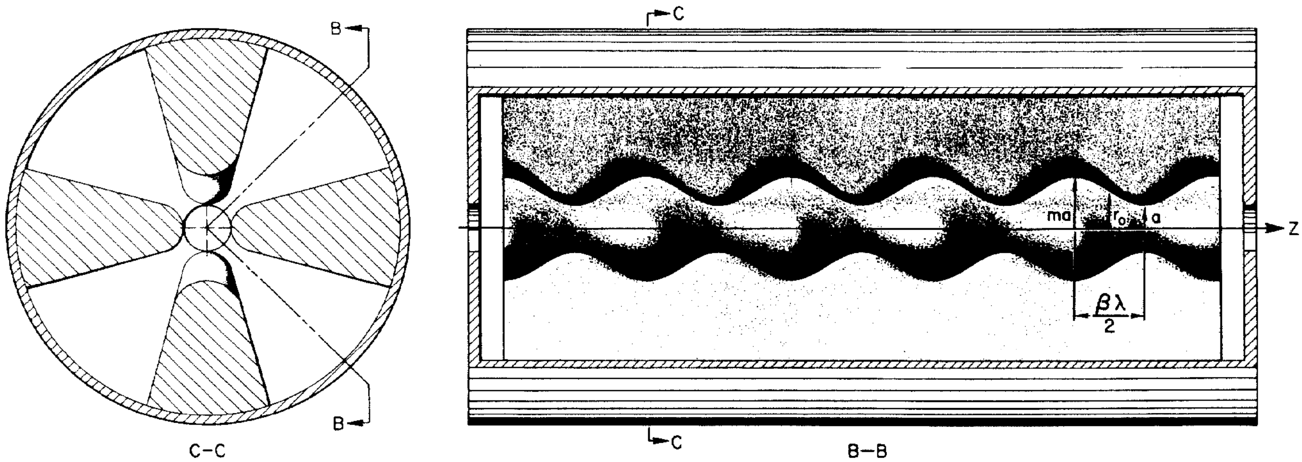

Fig. 2. Schematic drawing of RFQ resonator.

an overall strong focusing effect. The transverse forces at a given time are spatially continuous along the z-axis. If the pole tips have a constant radius, only a transverse focusing force is present. In Fig. 2, the pole tips have a sinusoidal-like variation in radius of ma to a, as one goes along the $\beta\lambda/2$ unit cell. 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.

In conventional drift-tube linacs, the focusing force, which is obtained from magnetic quadrupoles within the drift tubes, becomes too small at low velocities to confine the beam, especially at high beam currents. The RFQ can operate at a velocity below that of conventional linacs because the focusing is obtained from the velocity-independent electric force. The operation of a linear accelerator at low velocities permits adiabatic bunching of the dc input beam within the linac structure, resulting in high capture and transmission efficiencies (>90%). Adiabatic bunching is not restricted to low energy in principle, but its application at high energies becomes too costly in length. If the bunching and accelerating functions are combined, so that the adiabatic bunching is done while the beam is accelerated, the space-charge limit can be raised significantly (compared with the conventional approach, in which the beam is first bunched before injection into a linac accelerator). Furthermore, the high capture efficiencies obtained with the RFQ make efficient use of the ion-source output beam.

The strong focusing from the electric field, together with the combined-function adiabatic bunching, results in a high space-charge limit, even though the dc injection voltage may be as low as 20 to 50 kV. An output ion-beam energy in the 1-MeV/nucleon range typically is obtained within a few meters.

In comparison with a dc accelerator at the same beam current and output energy, the RFQ frequently offers the advantage of a much reduced size. The RFQ's strong focusing forces allow large beam currents with good output beam quality; the beam-current capacity of the RFQ appears to be greater than most dc accelerators. The RFQ offers greater flexibility than dc accelerators in the use of ion sources. A physically large and complex ion source for either positive or negative charge can be used as an injector. For convenient operation of the ion-source, it is possible to apply a bias dc voltage to the RFQ, so that the ion source is at ground potential. Also, because the RF amplitude is the only physical parameter to be adjusted, the RFQ is relatively simple to operate. Some disadvantages are (1) the RFQ is probably less flexible than dc accelerators for output energy variation and (2) for energies greater than about 2 MeV/ nucleon, the average accelerating field is less than that for a conventional linac. However, extending RFQ operation to higher energies does not degrade the beam performance; and, for low duty-factor applications, can result in less total power consumption than for a conventional linac with dc focusing magnets.

Thus, an RFQ 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 about 1 MeV/nucleon in a few meters. 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.[7] A four-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 Wideröe resonant system could be used; or with very low frequencies suitable for heavy ions, an externally resonant structure[9] may become useful. A multiple beam channel RFQ has been suggested by Swenson.[9] If the current capacity of a single RFQ channel is not sufficient, a multichannel RFQ array and the funneling technique[9] could be used to increase the total current to higher values.

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 3 summarizes our procedure. Electric fields obtained from the potential function were used to construct transformations for the beam-dynamics simulation program PARMTEQ.[2,3] 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 the radius of curvature in the transverse plane, both as a function of z. In the center of the unit cell, the pole tips have quadrupolar symmetry with both the radius and the radius of curvature equaling r_0. The pole tips are constructed by generating a data file on paper tape that is used as input to a numerically controlled milling machine.

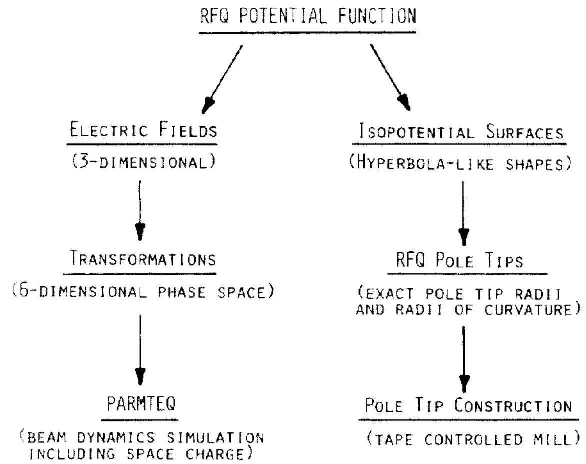

Fig. 3. Beam-dynamics simulation and pole-tip shape.

Beam-Dynamics Design Procedures for RFQ Systems

The methods used to synthesize RFQ systems to meet specific objectives have been described previously.[3] Figure 4 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

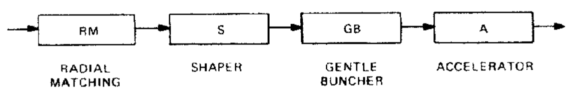

Fig. 4. RFQ functional block diagram.

section, where the radial focusing strength is increased from a low initial value to a higher final value in ~ 2-5$\beta\lambda$. 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 starts at -90° and increases 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.

A design constraint is imposed that makes the average radius of the pole tips r_0 constant, except in the radial-matching section. This keeps 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. However, in some applications the value of B has been made to decrease linearly by increasing r_0 through the accelerator section. This increases the average size of the beam, reduces its divergence, and tends to facilitate radial matching into the next linac.

Applications of the RFQ

The great flexibility inherent in the RFQ concept suggests its use in a wide variety of accelerator systems. After the successful proof-of-principle test, there has been a rapidly increasing interest in the RFQ. It has been accepted for inclusion in several accelerator systems being studied, designed, or constructed at Los Alamos. Also, we have been asked by many Laboratories to provide guidance for RFQ use in existing or proposed accelerators. Table 1 summarizes the Los Alamos applications, as well as the expanding interest in applications for other Laboratories. Major categories are injection systems for proton or heavy-ion synchrotrons, plasma heating and diagnostics, low-energy research accelerators, and heavy ion fusion. Los Alamos is working with CERN in a joint effort to construct an RFQ linac to provide a 515-keV proton beam for CERN's "old" 200-MHz injector linac.

Table 1

RFQ Linac Applications*

Los Alamos	
PIGMI Protoype	LAMPF Injector
FMIT Prototype	Research Accelerator
Heavy Ion Medical Accel.	Plasma Heating
Heavy Ion Fusion Research	Particle Beam Research
Other Laboratories	
BNL - AGS Injector	CRNL - ZEBRA
- Plasma Heating	KfK - SNQ
- Tritium Generator	- Plasma Heating
LBNL - Medical Accelerator	GSI - UNILAC
NBS - Neutron Sources	Frankfurt - HI Fusion
PPPL - Plasma Diagnostics	Tokyo - NUMATRON
CERN - PS Injector	

*The RFQ linac has been accepted or is under consideration for inclusion in these projects that are being constructed, proposed, or studied.

In the following sections we discuss three RFQ beam-dynamics designs. Each linac will be discussed briefly, and most of the details will be presented in tabular form. The currents listed in the tables are the microscopic-averaged electrical currents and thus correspond to the average current for 100% duty factor. The current limit listed was calculated from the formulas given by Wangler.[10] The emittances are normalized values and are to be multiplied by π to obtain the ellipse area in cm-mrad units. The quantity E_s is the assumed maximum surface electric field; L is the cumulative RFQ length from the input. The quantities a and m are defined in Fig. 2.

FMIT Prototype RFQ

The Fusion Materials Irradiation Test accelerator[11] is being designed by Los Alamos for the Hanford Laboratory. The 35-MeV deuteron beam from this linac will bombard a lithium target to produce neutrons for testing fusion-reactor materials. A prototype test will be carried out at Los Alamos. The prototype will consist of the injector, the RFQ, and a 3-MeV portion of the drift-tube linac. The RFQ will accelerate a 100-mA beam from 0.075 to 2.00 MeV in 3.88 m. The other parameters and the predicted performance are listed in Table 2.

Figure 5 is a computer-generated plot of the FMIT RFQ pole-tip shape in the x-z plane. Note that the transverse scale has been expanded, relative to the longitudinal scale. This plot also shows the relative lengths of the four functional sections. A large part of the total length is the shaper and gentle-buncher sections that are devoted principally to the bunching process. When the bunching length dominates an RFQ linac designed to produce a fixed final energy, we usually find that the overall length decreases with decreasing injection energy. This new situation places emphasis upon using the lowest possible energy into the RFQ, consistent with the capability of the ion source, to produce the required current.

Figure 6 shows the radial, phase, and energy profiles from a PARMTEQ beam-dynamics analysis. The input consisted of 360 particles with 75-keV energy, randomly distributed in the x-x', y-y' phase space, and uniformly distributed through 360^{o} of phase to represent a dc beam. At the top of the figure the x-coordinates of these particles are plotted at each cell. The dotted lines are plots of the quantity a, the size of the bore aperture. The middle plot shows the phase of the particles, and the dotted lines are the phase extent of the zero-current separatrix. The lower plot shows the energy of the particles at each cell. The dotted lines indicate the energy extent of the zero-current separatrix.

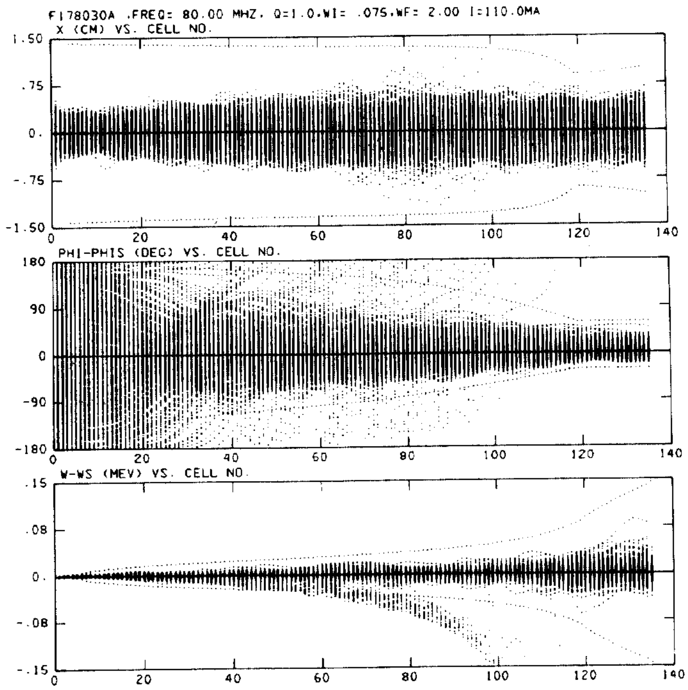

Fig. 6. FMIT prototype RFQ radial, phase, and energy profiles.

Table 2

FMIT Prototype RFQ

Ion: Deuteron

Frequency: 80 MHz

Nominal Current: 100 mA

Current Limit: 205 mA

PARMTEQ RESULTS

Input Current: 106 mA

Output Current: 100 mA

Emittance		
	Input (90%):	0.070
	Output (90%):	0.160
	Input (RMS):	0.017
	Output (RMS):	0.036

→ RM → S → GB → A →

W(MeV)	0.075	0.075	0.120	0.80	2.00
E_s(MV/m)	3.01	17.6	17.6	17.6	17.6
m	1.00	1.00	1.12	2.13	2.13
a(cm)	8.31	1.42	1.35	0.89	1.00
r_o(cm)	8.31	1.42	1.42	1.42	1.63
ϕ_s(deg)	—	-90	-72	-30	-30
E_o(MV/m)	0	0	0.40	1.97	1.31
V(kV)	185	185	185	185	185
B	0.20	6.82	6.82	6.82	5.20
L(m)	0	6.7	130	274	388

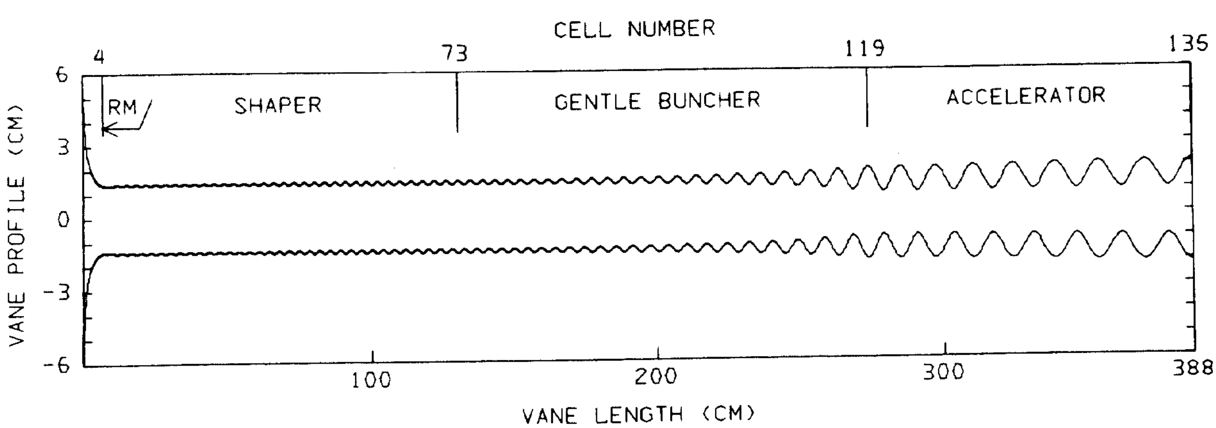

Fig. 5. FMIT prototype RFQ pole-tip shape.

PIGMI Prototype RFQ

During 1981, a prototype of the Pion Generator for Medical Irradiation[12] will be tested at Los Alamos. For this test, the RFQ is designed to accelerate a 30-mA proton beam from 0.030 to 1.50 MeV in 1.1 m. Table 3 lists the other parameters and the predicted performance.

Table 3

PIGMI Prototype RFQ

Ion: Proton		RM	S	GB	A	
Frequency: 440 MHz	W(MeV)	0.03	0.03	0.094	0.40	1.50
Nominal Current: 30 mA	E_s(MV/m)	7.2	40.6	40.6	40.6	40.6
Current Limit: 67 mA	m	1.00	1.00	1.15	2.14	2.17
PARMTEQ RESULTS	a(mm)	13.2	2.33	2.17	1.43	1.39
Input Current: 32 mA	r_o(mm)	13.2	2.33	2.33	2.33	2.33
Output Current: 29.8 mA	ϕ_s(deg)	–	-90	-60	-30	-30
Emittance Input (90%): 0.034	E_o(MV/m)	0	0	1.21	4.21	2.32
Emittance Output (90%): 0.040	V(kV)	70	70	70	70	70
Emittance Input (RMS): 0.008	B	0.20	6.38	6.38	6.38	6.38
Emittance Output (RMS): 0.009	L(cm)	0	1.1	32.6	55.2	110.8

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.

This RFQ linac is an improvement of a previously discussed system.[4] It accelerates a 50-mA beam of Xe^{+1} ions from 0.30 to 10.0 MeV in 27.7 m. Table 4 lists the other parameters and the predicted performance.

Table 4

Heavy Ion Fusion RFQ

Ion: Xe^{+1}		RM	S	GB	A	
Frequency: 12.5 MHz	W(MeV)	0.30	0.30	0.60	3.00	10.0
Nominal Current: 50 mA	E_s(MV/m)	4.9	20.0	20.0	20.0	20.0
Current Limit: 77 mA	m	1.00	1.00	1.08	1.53	1.54
PARMTEQ RESULTS	a(cm)	8.42	2.05	1.97	1.61	1.59
Input Current: 56 mA	r_o(cm)	8.42	2.05	2.05	2.05	2.05
Output Current: 52.3 mA	ϕ_s(deg)	–	-90	-68	-32	-32
Emittance Input (90%): 0.021	E_o(MV/m)	0	0	0.33	1.28	0.77
Emittance Output (90%): 0.051	V(kV)	303	303	303	303	303
Emittance Input (RMS): 0.005	B	0.20	3.37	3.37	3.37	3.37
Emittance Output (RMS): 0.011	L(m)	0	0.11	9.75	16.6	27.7

Acknowledgments

We acknowledge the support and guidance of E. A. Knapp, R. A. Jameson, and D. A. Swenson. We thank colleagues from Los Alamos and many other Laboratories for their encouragement and technical advice.

References

1. I. M. Kapchinskii and V. A. Teplyakov, "Linear Ion Accelerator with Spatially Homogeneous Strong Focusing," Prib. Tekh. Eksp. 119, No. 2, 19-22.
2. R. H. Stokes, K. R. Crandall, J. E. Stovall, and D. A. Swenson, "RF Quadrupole Beam Dynamics," Proc. 1979 Particle Accelerator Conf., March 12-14, 1979, San Francisco, California, IEEE Trans. Nucl. Sci., NS-26, 3469.
3. K. R. Crandall, R. H. Stokes, and T. P. Wangler, "RF Quadrupole Beam-Dynamics Design Studies," Proc. 10th Linear Accelerator Conf., Montauk, New York, September 10-14, 1979 (Brookhaven National Laboratory, Upton, NY, 1980), BNL-51134.
4. T. P. Wangler and R. H. Stokes, "Application of the RF Quadrupole in Linear Accelerators for Heavy Ion Fusion," Proc. Heavy Ion Fusion Accelerator Study, Berkeley, California, October 29 to November 9, 1979.
5. 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, "The Radio-Frequency Quadrupole: General Properties and Specific Applications," Proc. XIth Int. Conf. on High-Energy Accelerators, CERN, Geneva, July 7-11, 1980.
6. T. P. Wangler and R. H. Stokes, "The Radio-Frequency Quadrupole Linear Accelerator," Proc. 6th Conf. on the Application of Accelerators in Research and Industry, North Texas State Univ., Denton, Texas, November 3-5, 1980.
7. J. M. Potter, S. W. Williams, F. J. Humphry, and G. W. Rodenz, "Radio-Frequency Quadrupole Accelerating Structure Research at Los Alamos," IEEE Trans. NS-26, 3745 (1979); J. M. Potter, "An RF-Power Manifold for the Radio-Frequency Quadrupole Linear Accelerator," Proc. 10th Linear Accelerator Conf., Montauk, New York, September 10-14, 1979 (Brookhaven National Laboratory, Upton, NY, 1980), BNL-51134.
8. J. E. Stovall, K. R. Crandall, and R. W. Hamm, "Performance Characteristics of a 425-MHz RFQ Linac," Proc. 6th Conf. on the Application of Accelerators in Research and Industry, North Texas State Univ., Denton, Texas, November 3-5, 1980.
9. D. A. Swenson, "RF Linac Approach to Heavy Ion Fusion," Proc. Heavy Ion Fusion Accelerator Study, Berkeley, California, October 24-November 9, 1979.
10. T. P. Wangler, "Space-Charge Limits in Linear Accelerators," Los Alamos Nat. Lab. report LA-8388.
11. D. J. Liska and M. D. Machalek, "FMIT--The Fusion Materials Irradiation Test Facility," Proc. of 6th Conf. on the Application of Accelerators in Research and Industry, North Texas State Univ., Denton, Texas, November 3-5, 1980.
12. T. J. Boyd et al., "The PIGMI Technology," Los Alamos National Laboratory unpublished report.