IEEE Transactions on Nuclear Science, Vol. NS-30, No. 4, August 1983

OPERATING CHARACTERISTICS OF A 2.0-MeV RFQ*

F. O. Purser, E. A. Wadlinger, O. R. Sander, J. M. Potter, and K. R. Crandall, AT-2, MS H818
Los Alamos National Laboratory, Los Alamos, NM 87545

Summary

A second radio-frequency quadrupole (RFQ) accelerator has been designed, constructed and operated at Los Alamos National Laboratory. The accelerator's design parameters represent a major extension from the original Los Alamos RFQ,[1] with the new accelerator being 2.5 times as long, having three times the output energy, and with 2.5 times the current limit. The new accelerator's operating characteristics were studied for 3 months before disassembly to incorporate design modifications. Results are discussed.

Introduction

Construction and operation of the new accelerator have led to increased knowledge and insight into RFQ properties in three major areas. The first of these, involving rf tuning properties of an RFQ structure, is dealt with fully in a paper at this conference[2] and will be touched on here only as the end results affect operating characteristics. Second, in the process of coupling rf power into the system, apparently ideal conditions were set up to induce and support a new RFQ voltage breakdown mode that subsequently received a considerable amount of study. Finally, the new accelerator was operated on an extensively instrumented accelerator test stand that allowed its operating characteristics to be measured accurately to serve as a test of the computer programs used to both design and predict performance.

Accelerator Tune Characteristics

The design specificiations of the RFQ are given in Table I. Of these, the added length proved to be a major departure from the original proof-of-principle (POP) design. After initial difficulties in tuning the quadrupole mode to the proper accuracy, an analysis[2] indicated the source of the problem. Briefly, in tuning the rf structure, errors in vane positioning influence vane voltage by their effect upon the structure's local capacitance. This effect can be parameterized by Eq. (1).

$$\frac{\delta V}{V_0} = -\frac{1}{6}\frac{L^2}{\lambda_0^2}\frac{\delta C}{C} \quad . \tag{1}$$

Note the L^2 dependence where L is the vane length, and λ_0^2 is the electrical wavelength. If one substitutes the appropriate values for the present RFQ, assuming only that $\delta C/C \sim -\delta g/g$ where g is the average intervane gap, then if one wishes to hold the intervane voltage error to less than 10%, it follows that the vane position error must be held to less than 0.0025 mm. For a 3-m-long structure this proved to be a difficult positioning problem, particularly because there were machining errors in the vanes themselves exceeding 0.125 mm. At this juncture, we decided to tune the structure to the best field possible and to operate it in this condition to study

TABLE I

ATS RFQ DESIGN PARAMETERS

Frequency	425 MHz
Ion	H^-
Number of cells	356
Length	289.23 cm
Vane voltage	111.34 kV
Average radius, r_0	0.394 cm
Final radius, a_f	0.270 cm
Final modulation, m_f	1.830
Initial synchronous phase, ϕ_i	-90°
Final synchronous phase, ϕ_f	-30°
Peak surface field	41.4 MV/m (2.06 Kilpatrick)
Nominal current limit	167 mA
Nominal acceptance at 100 mA	0.232π cm•mr (normalized)

the effect of vane voltage errors on operating parameters. The final longitudinal quadrupole field distributions are shown in Fig. 1. Voltage variations of ∿50% existed along the structure's length.

Ion Arcing

The accelerator was installed on the accelerator test stand and waveguide coupled to a 1.25 MW klystron power source. In the initial stub tuning of the waveguide, the cavity was left slightly undercoupled ($\beta < 1.0$), and a low-Q waveguide cavity was created by placing the stubs too far from the window, slowing down the time response.

After rf conditioning the accelerator for 1 wk, it was sustaining design power levels. The system underwent a normal rf conditioning with attendant cleanup sparking with no difficulty. After thorough rf conditioning, beam was injected into the accelerator. The beam injection triggered a complete rf short circuit; that is, reflected power equaled incident power. Input beam power as low as 1 pW proved as effective as larger beam currents in triggering total power reflection. As soon as beam current was interrupted, rf power was restored. This behavior persisted for rf power levels ranging from 5 W to 700 kW.

Initially we suspected electron multipactoring as the source of the observed behavior, but eventually

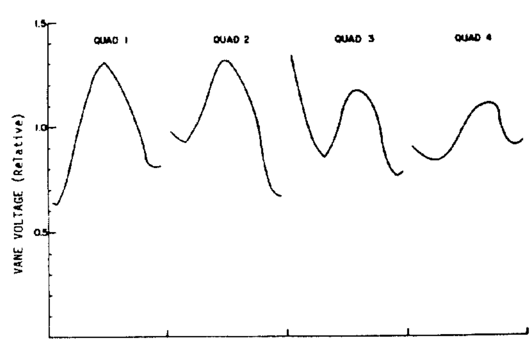

Fig. 1. Final intervane voltages as a function of longitudinal position. The distributions in each quadrant are normalized to 1.0.

*This work was supported by the US Dept. of Defense, Defense Advanced Research Projects Agency, and Ballistic Missile Defense Advanced Technology Center.

this was ruled out. Voltage and gap lengths at all suspect areas such as the vane to end-tuner gap, coupling slots, and manifold capacitors would not sustain multipactoring at the voltages at which breakdown occurred. Studies of electron orbits for the intervane gaps themselves indicated a degree of instability that would not support multiplication. In addition, electron multipactoring is a self-sustaining phenomenon that usually does not cease when beam is turned off.

The mechanism that we believe explains the breakdowns was proposed by Paul Channell at Los Alamos. His studies of ion orbits in the vane gaps indicated very stable, self-focusing discharges that could produce sufficient power loss to provide the short circuit causing the observed total power reflections. The ion (in this case, proton) orbits are shown in Fig. 2. After being initiated by the beam, these discharges propagate along the entire vane length and eventually self-quench from the hydrogen exhaustion of the substrate that produces the protons for multiplication. In our initial tune, the power system's time response under loading was inadequate to force this breakdown to the quench point. Tuning to produce a slightly overcoupled condition eliminated ion arcing as a problem.

RFQ Performance

The accelerator test stand is equipped with a high brightness, pulsed, negative ion source;[3] several computerized emittance scanners located both before and after the RFQ; and appropriately suppressed Faraday cups at various locations for measuring pulsed beam currents. Its principal deficiency at present is the absence of a magnetic analyzing system for beam-energy analysis.

Both the ion source and the rf power system operate in a pulsed mode. The ion source operates at a 5-Hz frequency with pulse lengths varying from 0.5 to 1.25 ms; whereas the rf power system was operated with pulse lengths varying from 1.0 ms down to 0.1 ms, also at 5 Hz. Output beam currents from the ion source ranged from 80- to 150-mA peak current, with beam currents injected into the RFQ varying from 35.0 mA down to near zero. Average pulsed-power levels in the RFQ were varied from 100 kW to somewhat in excess of 650 kW, which may be compared to the design power level of 550 kW.

Our experimental program was slanted toward measurements that would permit direct tests of the computer codes used at Los Alamos to model RFQ performance.[4] Given the RFQ's existing (measured) field distribution and the input emittance and phase-space orientation, beam current, and energy, the code PARMTEQ can be used to predict various output beam parameters as functions of RFQ power level. Of these, we have measured total transmission efficiency, input and output beam emittances, and transmitted current above various threshold energies. Even without energy-spectrum analysis, these latter measurements can be used to confirm the predicted (by PARMTEQ) energy distributions because of the transmission characteristics of the retarding foils used in the threshold Faraday cups.

In Fig. 3 the predicted and measured total beam transmission efficiencies are plotted. The dashed curve in the figure indicates the transmission that would have been expected if the RFQ fields could have been properly tuned. The abscissa in the figure is the ratio of actual RFQ power to the 550-kW design power level. Maximum beam current accelerated by the RFQ thus far has been 18 mA.

Figure 4(a) shows the transmission curve for one of the energy-retarding foils used in the threshold Faraday cup as a function of monoenergetic incident beam energy. Figure 4(b) displays the output beam energy distributions predicted by PARMTEQ for several rf power levels. By convoluting the energy distribution and the foil transmission function, one can obtain a measurement prediction for the threshold cup for this particular foil. In Fig. 5 we show the results of a series of such measurements compared to the code predictions. Although the agreement is not perfect, the results are quite good when one considers the sensitivity of the output energy distribution to variations in rf power.

RFQ Voltage Levels

One of the points of interest in the present measurements is the voltage-holding ability of the RFQ linac configuration. Our original design intervane voltage was 111.34 kV, which resulted in voltage gradients of 41.4 MV/m or 2.06 times the Kilpatrick spark criterion[5] for our frequency and geometry. Because of the very nonuniform longitudinal voltage

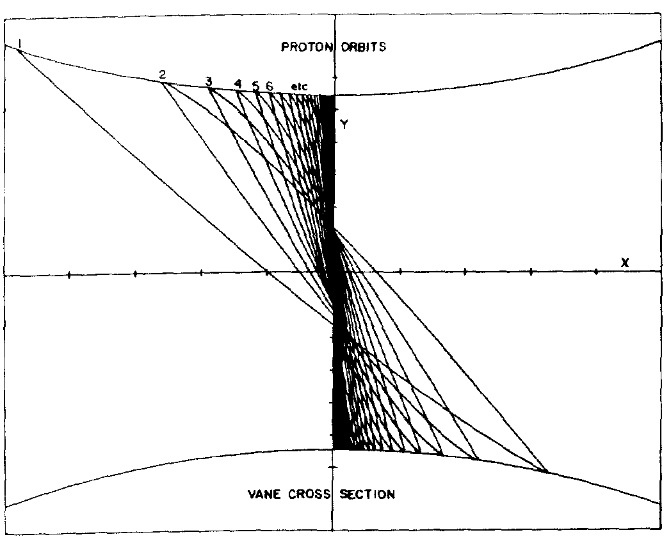

Fig. 2. Computer plot of the ion trajectories showing their stability and that they collapse rapidly to the vane center. This view looks along the RFQ axis.

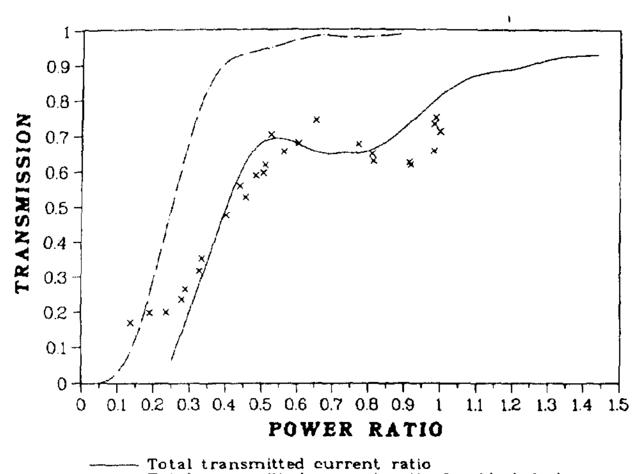

Fig. 3. Calculated and measured total transmission through the RFQ. The dashed curve represents the RFQ's expected transmission if field errors could have been eliminated.

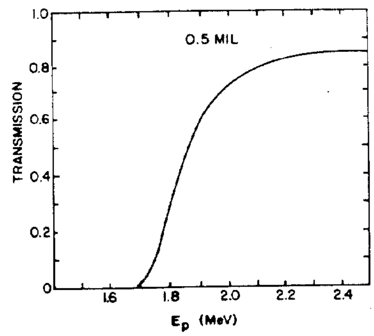

Fig. 4(a). Measured transmission curve for the 0.5-mil retarding foil of the threshold Faraday cup.

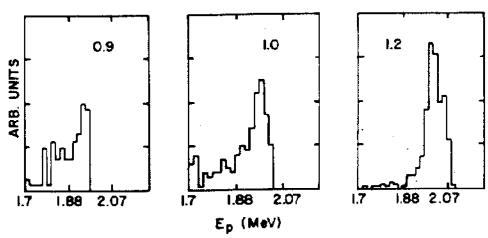

Fig. 4(b). Calculated output energy distributions for the RFQ at power levels of 0.9, 1.0, and 1.2 times the design power.

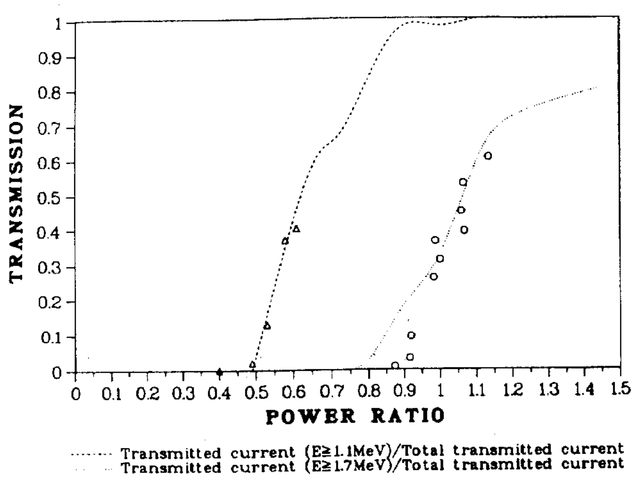

Fig. 5. Calculated transmissions through threshold Faraday cups for beam energies greater than ∿1.1 MeV compared with measured transmissions.

distributions in the RFQ quadrants, we have exceeded this design voltage substantially at higher power levels. Figure 6 shows the voltage gradients in the RFQ's four quadrants, divided by the Kilpatrick "limit" for the highest power level at which data were taken. Our experience indicates that maximum sustainable voltage in this configuration is somewhat a function of rf pulse length. Up to 2.5 times Kilpatrick, pulse lengths of 1.0 ms or greater were possible. As voltage gradients approached 3.0 times Kilpatrick, sustainable pulse lengths gradually shortened until, at the upper end of our range, operation was limited to ∿0.1-ms pulses. These voltage levels were sustained in vacuums that normally measure 5.0 x 10^{-8} in the body of the RFQ. Our ability to sustain these voltage gradients indicates that

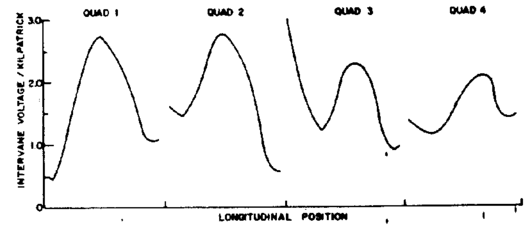

Fig. 6. A near repeat of Fig. 1, except that intervane voltages are calculated with 625.0-kW average power in the RFQ; resulting vane voltages have been referenced to the Kilpatrick spark criterion.

the original choice of a 2.06 Kilpatrick design voltage level is rather conservative.

Conclusion

Our studies on an RFQ with large field errors confirm this linac structure's ability to produce usable beam in the face of very adverse conditions. In addition, the experimental results provide confirmation of our ability to predict this structure's performance with our present computer codes.

This RFQ is at present being modified to eliminate most tuning difficulties encountered with its very long structure. In addition to minor mechanical changes, vanes with machining errors are being remachined to eliminate such errors, and dipole shorting rings modeled after those used on the Berkeley RFQ[6] are being installed. With these changes we anticipate operation at design parameters.

References

1. J. E. Stovall, K. R. Crandall, and R. W. Hamm, "Performance Characteristics of a 425-MHz RFQ Linac," Proc. 6th Conf. on Applications of Accelerators in Research and Industry, Denton, Texas, November 3-5, 1980, IEEE Trans. Nucl. Sci. 28, p. 1508 (1981).

2. J. M. Potter, F. O. Purser, and F. J. Humphry, "Radio-Frequency Quadrupole Tuning Experience," Proc. 1983 Particle Accel. Conf., Santa Fe, New Mexico, March 21-23, 1983 (1983).

3. P. W. Allison, H. V. Smith, Jr., and J. D. Sherman, "H- Ion Source Research at Los Alamos, "Proc. 2nd Int. Symp. on the Production and Neutralization of Negative Hydrogen Ions and Beams, Upton, New York, October 6-10, 1980, Brookhaven National Laboratory report BNL-51304, p. 171 (1981).

4. K. R. Crandall, R. H. Stokes, and T. P. Wangler, "RF Quadrupole Beam-Dynamics Design Studies", Proc. 1979 Linear Accelerator Conf., Montauk, New York, September 10-14, 1979, Brookhaven National Laboratory report BNL-51134, p. 205 (1980).

5. W. D. Kilpatrick, "A Criterion for Vacuum Sparking Designed to Include Both R.F. and D.C.," Rev. Sci. Inst., Vol. 28, p. 824 (1957).

6. P. Howard and H. Lancaster, "Vane Coupling Rings, A Simpler Technique for Stabilizing a Four-Vane Radio Frequency Quadrupole Structure," Proc. 7th Conf. on Applications of Accelerators in Research and Industry, Denton, Texas, November, 1982.