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PERFORMANCE CHARACTERISTICS OF A 425-MHz RFQ LINAC*

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Summary

A radio-frequency quadrupole (RFQ) focused proton linac has been developed and successfully tested at the Los Alamos Scientific Laboratory (LASL) for the purpose of evaluating its performance and applicability as a low-beta accelerator. The geometry of the structure was designed to accept a 100-keV beam, focus, bunch, and accelerate it to 640 keV in 1.1 m with a high-capture efficiency and minimum emittance growth. The accelerator test facility includes an injector, low-energy transport section for transverse matching, and a high-energy transport section for analysis of the beam properties. The accelerator cavity is exited through a manifold powered by a 450-MHz klystron. Diagnostic instrumentation was prepared to facilitate operation of the accelerator and to analyze its performance. Measurements of the beam properties are presented and compared with the expected properties resulting from numerical calculations of the beam dynamics.

Introduction

An RFQ focused linac structure was proposed as the low-energy section for two accelerator projects now under development at LASL. These projects include a deuteron accelerator for a Fusion Materials Irradiation Test Facility (FMIT) and a proton linac to serve as a Pion Generator for Medical Irradiation (PIGMI). Before these projects could be committed to this new and untested concept,[1] a successful demonstration of a prototype RFQ accelerator was required.

An RFQ structure was designed to take advantage of an existing 450-MHz RF power stand and an associated resonant cavity. An existing ion source, accelerating column, and beam line were modified to inject a 100-keV proton beam into the test accelerator and to transport and analyze the 640-keV accelerated beam. Success of the demonstration prototype was to be decided upon verification of the final beam energy, emittance growth and transmission-efficiency measurements, and on the stability of operation at design power and beam current. The general features of the accelerator test stand are shown in Fig. 1, along with a summary of the linac and measured beam parameters.

Energy Measurements

The only adjustable parameter in the RFQ itself is the intervane voltage. The structure is an excellent transport element, transmitting some beam, even at very low voltages. As the intervane voltage is increased, the transmitted beam current increases almost linearly and becomes partially accelerated. At a threshold level of about 50% of the design voltage, a small fraction of the beam is captured

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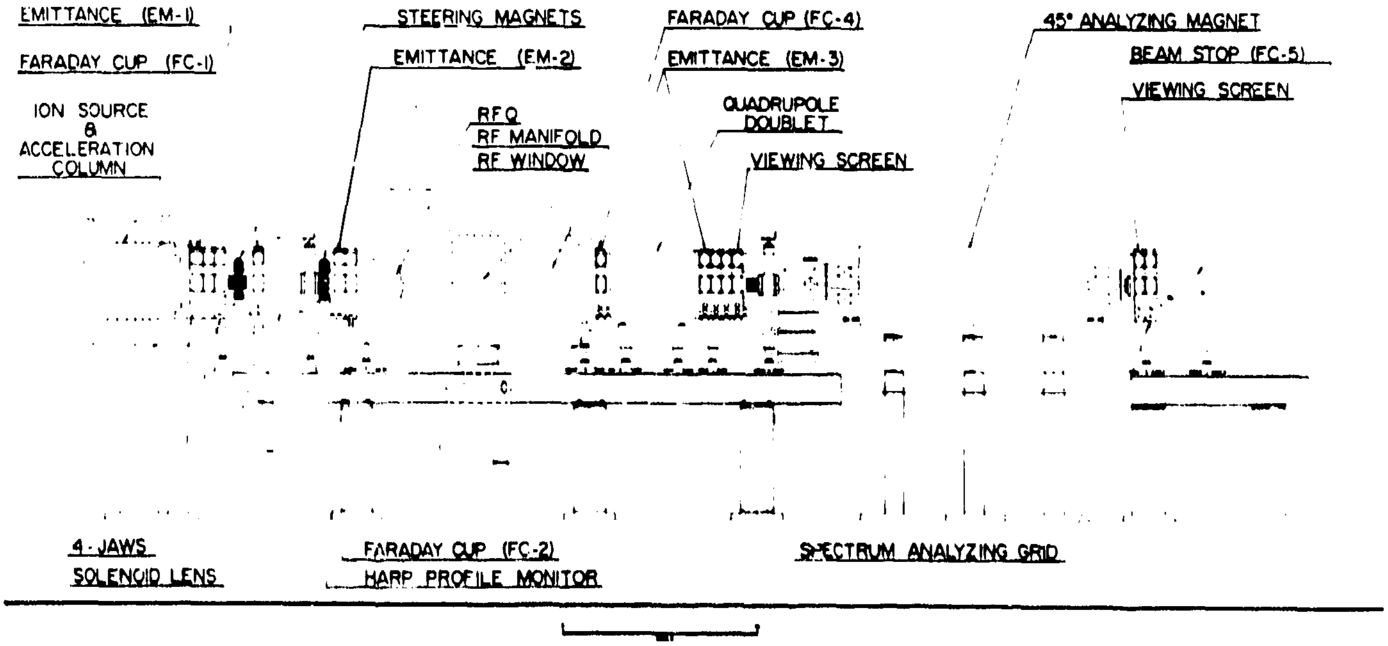


LINAC PARAMETERS

INJECTION ENERGY	100 keV
FINAL ENERGY	640 keV
FREQUENCY	425 MHz
INTERVANE VOLTAGE	44 kV
BORE RADIUS	2.00-1.28 mm
VANE LENGTH	110.84 cm

BEAM PARAMETERS

FINAL CURRENT	26 mA
PULSE LENGTH	~20 μs
REPITITION RATE	15-360 Hz
CAPTURE EFFICIENCY	~87%
FINAL EMITTANCE (RMS NORMALIZED)	.03 cm-mr

Fig. 1. RFQ test stand.

longitudinally and is accelerated to the final 640-keV design energy. When this occurs, a measurement of the electric field in the manifold, (a cavity that couples power from the waveguide into the accelerating structure) provides a reference point for estimating the design RF field level in the RFQ.

As the vane voltage is further increased, the transmission is also increased; but, in addition, the longitudinal acceptance grows and a larger fraction of the beam is captured and accelerated to the final design energy, as shown in Fig. 2. The accelerated beam was measured in a Faraday-cup beam stop (FC-5) located downstream of a 45° analyzing magnet, whereas the total transmitted beam current was measured in an insertable Faraday cup immediately following the accelerator (FC-4 in Fig. 1). At the design vane voltage, the transmitted beam was carefully analyzed for low-energy components. Consistent with numerical calculations, which indicate that in the presence of space charge, stragglers become radially unstable, no low-energy components were found. Therefore, at design RF field levels, all beam emerging from the RFQ is fully accelerated.

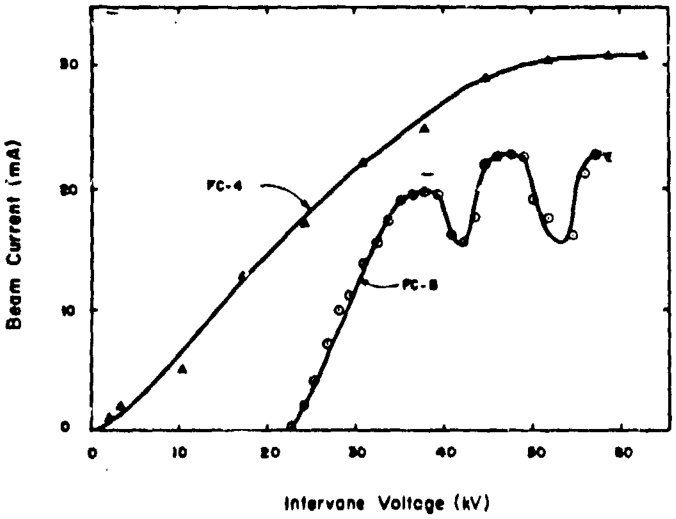
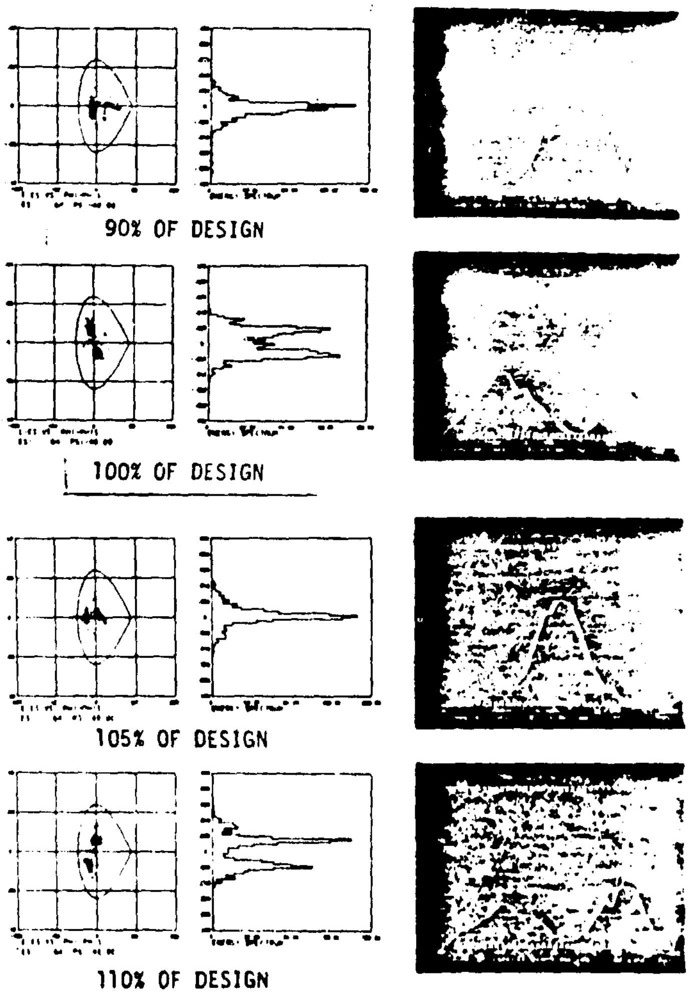


Fig. 2. RFQ transmission as a function of intervane voltage.

Because of a limited acceptance in the analyzing system, not all of the beam transmitted by the RFQ is transported to the beam stop (FC-5), which accounts for the difference between the maximum values of the two curves in Fig. 2. The peaks and valleys in the FC-5 curve are an artifact of this limited acceptance, and is the fact that variations in the energy spread of the beam are translated by the bending magnet into variations in the width of the beam.

Numerical simulation of the particle dynamics show that, for a 15-mA beam, the longitudinal phase space divides itself into two "hot" spots that oscillate about each other. The number of oscillations experienced is a function of the RF field amplitude. When the vane voltage is set to ~95% of the design level, the energy width is at a relative maximum. As the voltage is increased, the energy width becomes smaller and the amount of beam current transported to the beam stop increases. At approximately 112% of the design voltage, another relative maximum occurs in the energy spread, indicating 180° rotation of the beam in longitudinal phase space. This structure in the energy spectrum was observed and gives us an independent method of estimating the actual intervane voltage in the structure. Examples of the longitudinal dynamics and energy spectrums calculated numerically are compared with energy profiles, measured experimentally, in Fig. 3.


90% OF DESIGN

100% OF DESIGN

105% OF DESIGN

110% OF DESIGN

Fig. 3. Longitudinal phase space and energy spectrums, calculated and measured.

Field Measurements

The design voltage for this RFQ was based on a peak surface field that was 1.5 times the Kilpatrick limit. The performance characteristics of an RFQ can be improved significantly by designing to higher peak fields. It was of interest, therefore, to determine the sparking limit for our RFQ. Assuming that we are correct in our estimate of the design level, as explained above, we believe that the sparking limit in the neighborhood of 2.4 times Kilpatrick was achieved. We intend to base our future RFQ design on 2 times Kilpatrick.

Transmission Efficiency

The injected beam current was measured in an insertable Faraday cup (FC-2) located just ahead of the RFQ cavity; the output current was measured in a similar cup (FC-4) just following the linac. Transmission efficiencies were measured at the design RF field level for several injection currents (I_0). The results of these measurements are compared with those predicted by numerical calculations in Fig. 4. Because of the small entrance aperture (4-mm diam) of the RFQ, the matched beam was necessarily highly convergent in both transverse planes. The magnetic field of the solenoid, the single transport element preceding the RFQ, was therefore a very sensitive

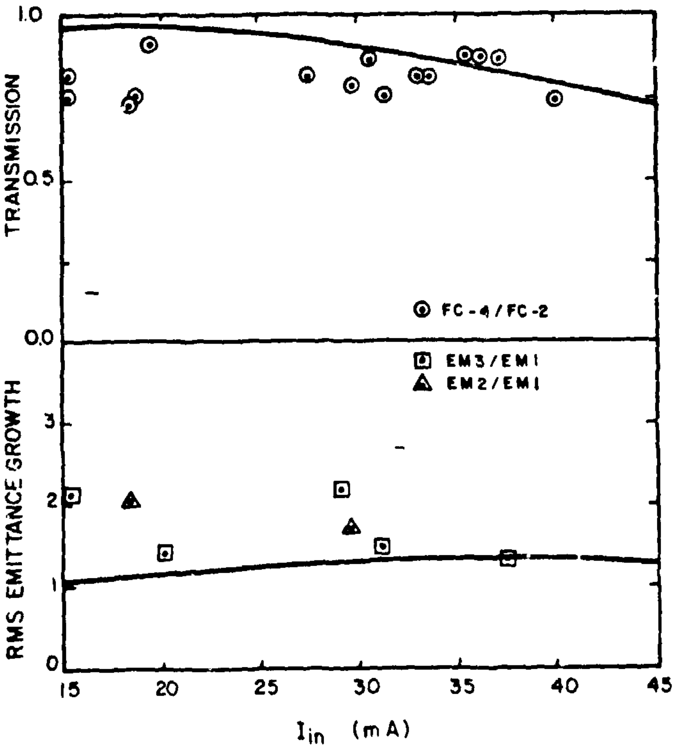


Fig. 4. RFQ transmission and emittance growth as a function of injected current.

parameter. As described above, all beam transmitted at design RF field levels was determined to be fully accelerated.

Emittance Growth

The total emittance of the accelerated beam is an important consideration when an RFQ is to serve as an injector to a subsequent structure. The rms emittance growth is considered to be a fundamental property of the structure and, in fact, is treated as a parameter in the design of RFQs. The initial (EM-1 and EM-2) and final (EM3) emittance were measured, using an automated slit-and-collector technique, with data simultaneously displayed and stored on disk. Emittance data gathered at design RF field levels for several injection currents (I_0). In analyzing the data, extraneous points caused by measurement noise were eliminated, as were contributions caused by H_2^+ and H_3^+ ion components in the beam. The resulting data were properly scaled and the first and second moments calculated for the distribution. The rms emittance quoted here is the area of an ellipse having the same rms properties as the measured distribution. If the distribution were uniform, the total emittance (E_{tot}) would equal four times the rms value (E_{rms}).

The RFQ structure is terminated in a full cell, having a vary narrow aperture in the vertical direction (2.52-m diam). The final beam is therefore highly divergent in one plane and exceeds the angular range of the measurement hardware in the vertical dimension. Emittance growth, for the horizontal plane, corrected for βγ is plotted as a function of injected current (I_0) and is compared with calculated values in Fig. 4. The accelerator operated best at the highest beam current available from the ion source, corresponding to the design case. Under these conditions the final normalized rms emittance was typically 0.011 cm·mr.

Conclusions

As indicated in Fig. 2-4, the RFQ test accelerator performed exceedingly well. In addition, it operated reliably at electric fields well in excess of its design. As a result of this test, RFQs are being designed for a wide variety of applications.

References

1. I. M. Kapchinskii and V. A. Teplyakov, "Linear Ion Accelerator with Spatially Homogeneous Strong Focusing," Pribory i. Tekhnika Eksperimenta, 119, No. 2, pp. 19-22, March-April 1970.