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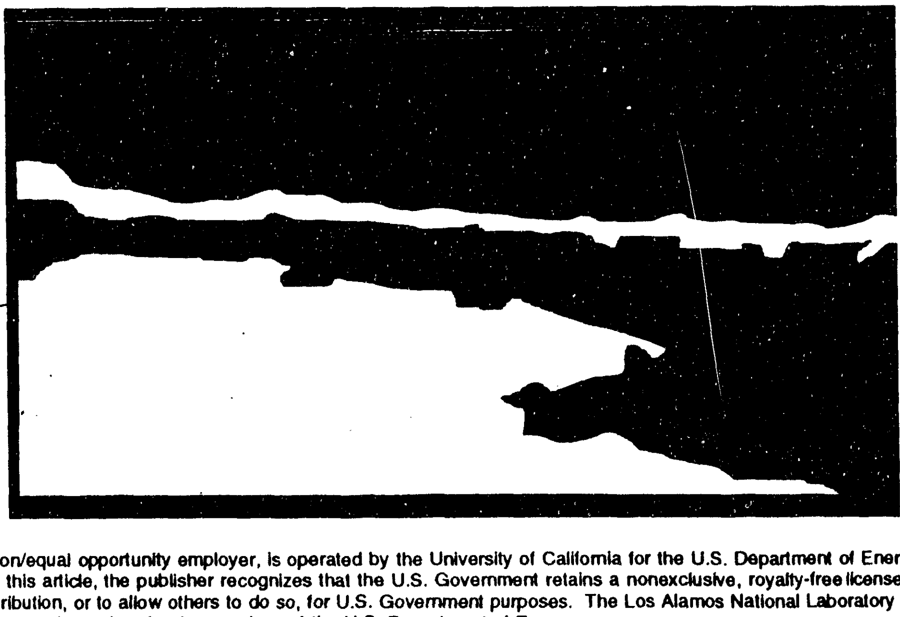

Los Alamos
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PERFORMANCE REPORT ON THE GROUND TEST ACCELERATOR RADIO-FREQUENCY QUADRUPOLE*

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Introduction

The Ground Test Accelerator (GTA) uses a radio-frequency quadrupole (RFQ) to bunch and accelerate a 35 keV input beam to a final energy of 2.5 MeV. Most measured parameters of the GTA RFQ agreed with simulated predictions. The relative shape of the transmission versus the vane-voltage relationship and the Courant-Snyder (CS) parameters of the output beam's transverse and longitudinal phase spaces agreed well with predictions. However, the transmission of the RFQ was significantly lower than expected. Improved simulation studies included image charges and multipole effects in the RFQ. Most of the predicted properties of the RFQ, such as input matched-beam conditions and output-beam shapes were unaffected by these additional effects. However, the comparison of measured with predicted absolute values of transmitted beam was much improved by the inclusion of these effects in the simulations. The comparison implied a value for the input emittance that is consistent with measurements.

Experimental Setup

The experimental setup consisted of an H^- injector, a low-energy beam transport (LEBT), the GTA RFQ, and a downstream diagnostics package. The H^- injector [1] was capable of producing 50 mA at the RFQ entrance. The LEBT contained two solenoids for varying the CS parameters at the RFQ entrance to determine the best match and contained two Lambertson steering magnets for varying the position and angle of the input beam. Diagnostics measured the input-beam current and the emittance midway in the LEBT during the RFQ operation and at the RFQ entrance location when the injector was rolled back.

The distinguishing characteristics of the RFQ are its cryogenic operating temperature (typically 20 to 35 K), its construction (copper plated aluminum), its peak fields (1.8 Kilpatrick or 36 MV/m at 425 MHz), and its intervane operating voltage (56 kV at 57 kW of cavity power) [1]. The residual dipole field is less than 1% of the quadrupole field at room temperatures and less than 3% at cryogenic temperatures. The RFQ was designed to produce 50 mA of beam with an output normalized root mean square emittance of 0.008 π cm mrad. The design input-beam current and emittance values are 55 mA and 0.006 π cm mrad respectively.

The diagnostics package [2] at the exit of the RFQ measured the output beam characteristics including the total transmitted and accelerated beam; the transverse and longitudinal emittances; the beam position, angle, and energy; and phase centroids.

The RFQ Performance and Initial Predictions

Most of the measured RFQ characteristics and the RFQ output beam agreed well with initial predictions [3]. We designed the RFQ for cw operation with liquid-hydrogen cooling and for 2% duty factor using the available GTA gaseous-helium cooling. We verified the cooling design by

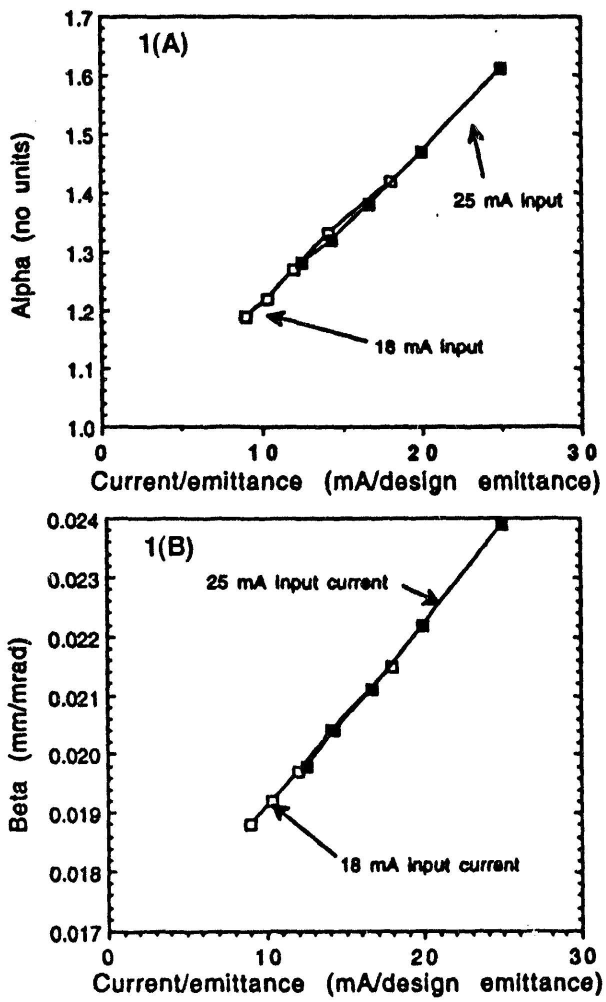

Fig. 1. Matched input values of the CS parameters (alpha, beta) versus the ratio on input current to emittance

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operating the RFQ without beam at 2% with a 2 ms rf pulse at 10 Hz. During beam studies we occasionally accelerated beam for 2 ms at 5 Hz. The predicted matched-beam CS parameters at the RFQ entrance showed a simple dependence on current and emittance (Figs. 1A and 1B). The best measured RFQ transmission occurred at the predicted values derived from these figures. The measured output CS parameters depended only on vane voltage and agreed with predicted values. The output emittance area depended on the vane voltage, the injector operating conditions, and the beam current and emittance. The smallest directly observed output emittance was between 0.013 and 0.014 π cm mrad; however, the highest output current occurred after a matching section and the first drift-tube linac (DTL) module (2.5 to 3.2 MeV) were attached to the exit of the RFQ. Therefore, no direct measurement of the RFQ emittance was possible with the highest current. The measured output emittance of the DTL module was between 0.013 and 0.015 π cm mrad. We expect that the RFQ emittance had a similar value because we anticipated no growth in either the matching section or the DTL module and little reduction in emittance from the 5% beam loss in the matching section. However, the highest output current of 37 mA with a transmission of 73% was lower than the predicted value of 87 to 92%. Because of our inability to obtain the expected current and transmission, we reexamined our simulations

GTA and Superconducting-Super Collider RFQ Simulations

We initially used only the quadrupole field and the lowest-order rf defocusing term [4] in our GTA-RFQ beam simulations because previous studies on different RFQ geometries showed that the higher-order effects were small. Since then additional simulations [5] have included the first eight terms [4] in the electric field potential and the effects of image charges. Most of the predicted beam parameters did not change. When we compared the two simulations of the GTA RFQ, we found that the mismatch factors [6]

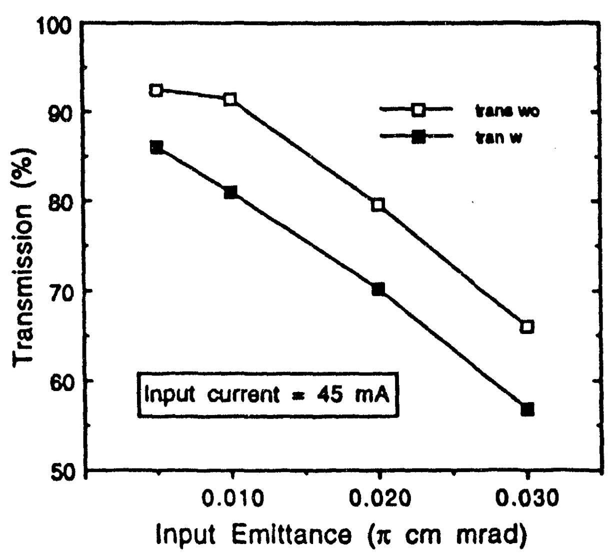

Fig. 2. Simulated (with and without higher order effects) GTA-RFQ transmission versus input emittance

between the two sets of CS parameters were typically only 0.05, often as low as 0.001, and never greater than 0.12. Similar comparisons of the longitudinal emittances also resulted in typically small mismatch factors of 0.11 an never greater than 0.14.

However, we reduced the GTA-RFQ simulated transmission by including the higher-order effects (Fig. 2).

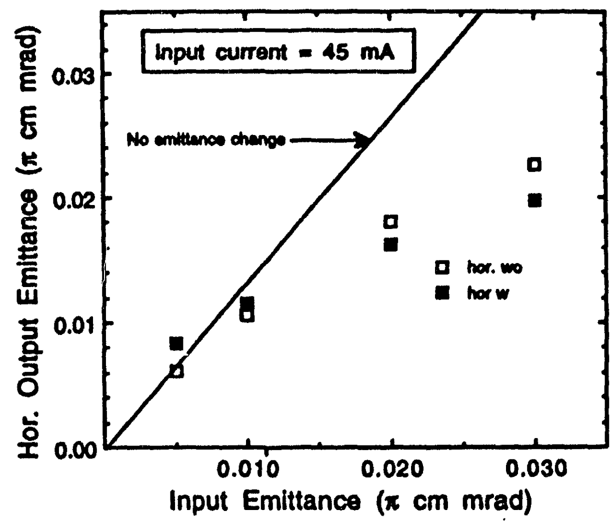

Fig. 3. Simulated (with and without higher order effects) GTA-RFQ output emittance versus input emittance.

The output-beam emittance area was also affected (Fig. 3). The higher-order effects increased the emittance growth for smaller input-emittance values, whereas, they decrease the output emittance for larger input values. We have not pursued an explanation for this behavior. In subsequent studies we found that the values chosen for the RFQ vane-tip radius, injection energy, frequency, and bore radius contributed to the strength of the higher-order effects.

The Superconducting-Super Collider (SSC) RFQ [7] design included the higher-order effects with trade-offs among minimizing the effects of multipoles, minimizing the peak surface fields, and maximizing the focusing effects on the beam. The input current and emittance were 30 mA and 0.02 π cm mrad. Compared with the GTA-RFQ, the final SSC-RFQ design [8] has a number of predicted. As shown in Figs 4A and 4B, the SSC-RFQ transmission should be higher. Note that the SSC-RFQ transmission is insensitive to the input emittance and significantly less sensitive to the input current. The SSC-RFQ output emittance is also relatively insensitive to the input-beam current (Figs. 5A and 5B).

Observations and Latest Predictions

From our best observed GTA transmission of 73%, the 51 mA input beam, and the simulations shown in Fig. 4A, we predicted that the input-beam emittance would be 0.012 to 0.013 π cm mrad. Using 0.013 to 0.015 π cm mrad as the estimated RFQ output emittance and the simulations in Fig. 5A, we predicted that the input emittance would be between 0.013 and 0.017 π cm mrad. With the injector rolled back, we had previously measured the emittance at both the midway station in the LEBT and at RFQ match point. We observed a 10 to 25% emittance growth between the two locations. When the best RFQ transmission occurred, we again measured the emittance at the midway station. From these measurements and the expected growth, we predicted that the input RFQ emittance would be 0.013 to 0.015 π cm mrad. The three predictions of the input RFQ emittance agree.

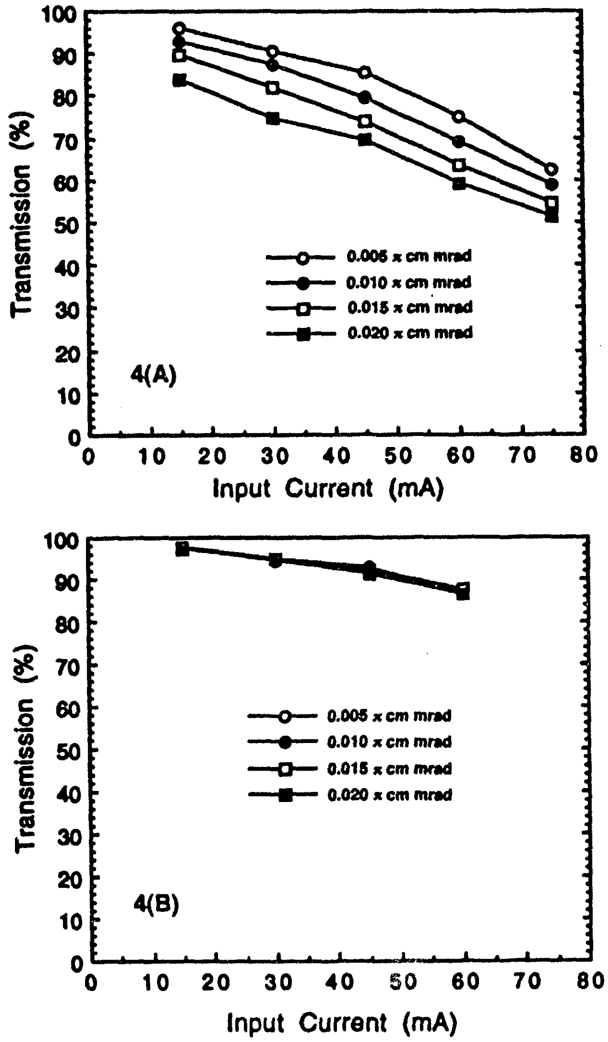

Fig. 4. Simulated GTA-RFQ transmission (A) and simulated SSC-RFQ transmission (B) versus input current for various values of input emittance.

Conclusions

We conclude that the effects of multipoles and image charges are important in the design of a high-brightness RFQ such as the GTA RFQ and that the inclusion of these effects in the SSC design has led to an RFQ that is significantly less sensitive to input-beam current and emittance. We find that when high-order effects are included in the simulations, the predicted transmission, input emittance, and output emittance of the GTA RFQ agree with observations.

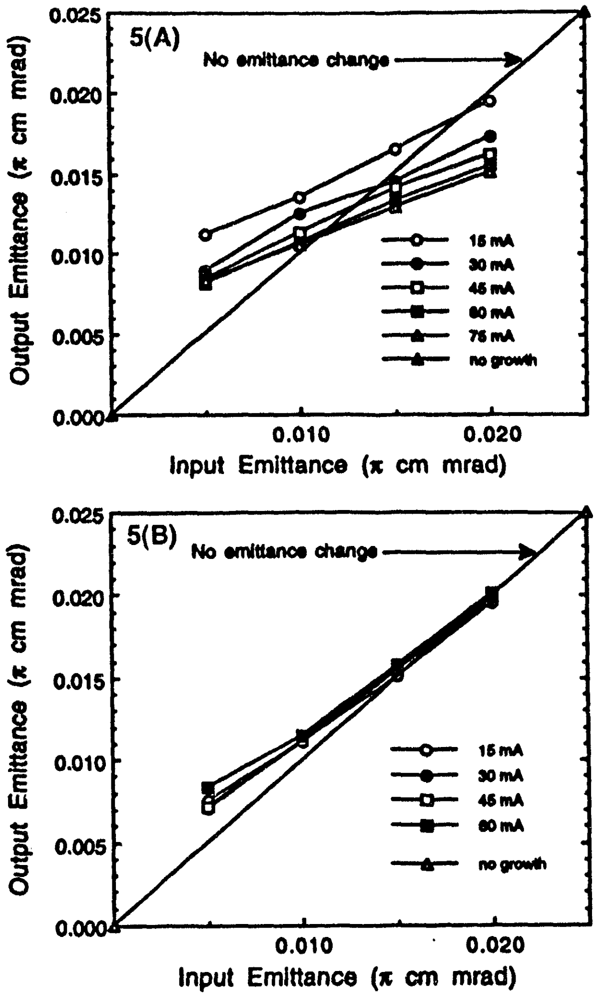

Fig. 5. Simulated GTA-RFQ output emittance (A) and simulated SSC-RFQ output emittance (B) versus input emittance for various input currents.

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