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COMPARISON OF SIMULATION WITH EXPERIMENT IN AN RFQ*

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Summary

The accelerator test stand (ATS) RFQ has provided an opportunity to compare the predictions of the RFQ beam-dynamics code PARMTEQ with actual operation of an RFQ. For this comparison, the code was adapted to simulate the measured operation parameters, which are somewhat different from those of the ideal design. A Monte Carlo code was written to provide input to PARMTEQ, based on measured input beam distributions. With these refinements, the code has given results that are in good agreement with measurements[1] and has provided information leading to an explanation of an unexpected set of measurements. This paper describes the method used to generate a pseudo particle beam based on the measured transverse properties of the RFQ input beam and describes some of the comparisons between simulation and experiment. An explanation is provided for the energy-spectrum structure observed in the RFQ output beam during low-voltage operation.

Introduction

Deviations from the ideal RFQ design provide a means to test the accuracy of PARMTEQ. Calculations made on a less-than-ideal machine should strain the assumptions made in the code and amplify discrepancies. However, before fair comparisons can be made, the code must include as many of the measured departures from the ideal machine as is possible. To this end, Crandall and Mills[2] have modified PARMTEQ to incorporate measured field errors that were caused by mechanical deviations from the ideal geometry. The ATS RFQ now operates at 413.25 MHz, almost 3% below the design frequency. This departure from design frequency is handled in the code by adding a line of code that permits an operating frequency (after the point that the RFQ has been generated) different from the design frequency. The reduction in frequency causes a reduction in the matched RFQ input beam energy (accommodated in PARMTEQ by changing another input line). The remaining problem is to simulate the measured transverse properties of the input beam.

Generating the Input Beam

The transverse properties are determined from scanner measurements.[3] These measurements provide matrices of signal strength corresponding to specific values of x and x' in the horizontal plane and y and y' in the vertical plane. No correlation information is available. The measurements in the x-x' plane can be considered as proportional to the probabilities that a particle will have $x=x_i$, $x'=x_j'$ in a rectangular region centered on the point (x_i, x'_j). The size of the region is determined by the scanner steps in x and x'. Assuming no correlation between the horizontal and vertical planes, the four-dimensional distribution information can be extracted by considering the x-x' and y-y' planes independently. For this assumption, it is easy to generate a distribution of macroparticle coordinates corresponding to the measurements, using standard Monte Carlo methods. The generated distribution is "real" in the sense that it is consistent with the measurements and uses all the information available from the measurements. However, the derived distribution is not equivalent to the physical distribution unless the two transverse planes are truly uncorrelated. For this reason we choose to refer to the generated distribution as "pseudo-real."

The pseudo-real coordinates are generated as follows. First x and x' coordinates are chosen randomly within their respective measured ranges, and the rectangle in which the point (x,x') lies is determined. Another random number in the range [0,1] is obtained. If this number is less than the probability of finding a particle in the point (x,x')'s rectangle, the point is accepted; otherwise, it is rejected and a new (x,x') point is tried. Once an (x,x') point is accepted, the same method is used to find a (y,y') point. This method populates the phase planes in accordance with the scanner measurements, but forces the rejection of large numbers of potential points because the probability of finding a particle in a given rectangle is quite small. To reduce the work for determining coordinates, the scanner-measurement matrices are reduced in size by removing border rows or columns that have no counts in them. If measurements with correlations between the x-x' and y-y' planes are made, this method will use too much computer time and another method will have to be found.

Once the coordinate sets are chosen, the individual coordinates are renormalized so that the coordinate distributions center on the average values of the measured distribution. Although this method chooses points in agreement with the measurements, it will not give the proper local densities if the number of points chosen is too small. A typical scanner run results in over 6000 individual values in a given two-dimensional plane. Even allowing for substantial numbers of zero values, proper local densities cannot be expected unless the number of pseudo points is at least of the same order. Figures 1 and 2 show good agreement between contours of the measured and derived distributions. In this case 50 000 pseudo points were generated to make up the pseudo-real input.

Comparison of Transmission

Some of the first data obtained from the ATS RFQ was a set of transmission measurements at different vane voltages. Pseudo-real input coordinates corresponding to the input beam for the measurements were

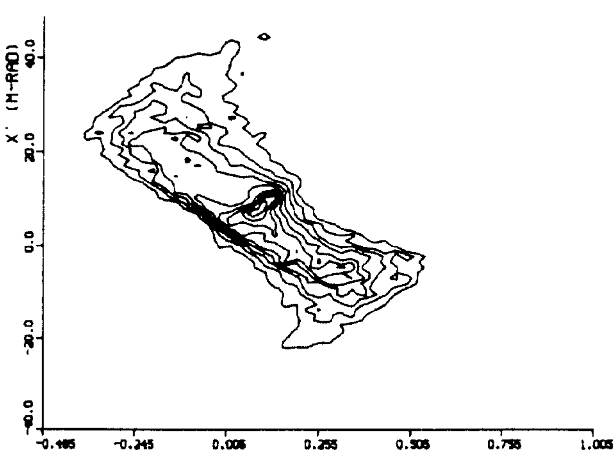

Fig. 1. Contour plot made from scanner measurements.

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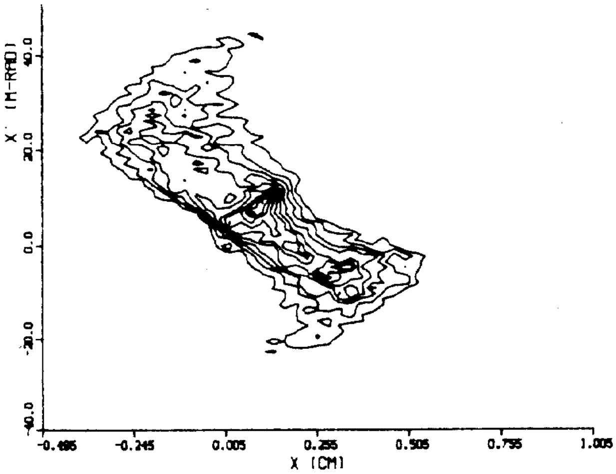

Fig. 2. Contour plot made from pseudo-real derived distribution.

used in PARMTEQ to compute a similar data set. The results shown in Fig. 3 are in good agreement.

Peaks in Energy Spectrum

Energy spectra measurements were made on some of the RFQ output beams obtained during the transmission study. These measurements led to the discovery that beam-energy distributions went from a single peak at the nominal output energy to a multiple-line spectrum as the operating voltage was decreased. This transition occurred between $V/V_0 = 0.90$ and $V/V_0 = 0.78$; V/V_0 is the ratio of the operating voltage to the design voltage. This observation was unexpected. However, when the computed PARMTEQ output beam was analyzed, it too showed a discrete spectrum below about $V/V_0 = 0.80$. Moreover, the position of the calculated peaks agreed with the measured positions.

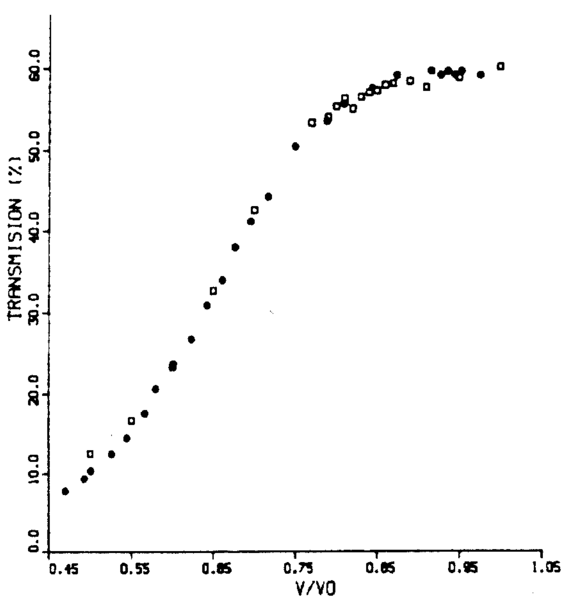

Fig. 3. Transmission versus V/V_0 for ATS RFQ operating at 413.25 MHz. Squares are computed; circles are measured.

Figure 4 shows an oscilloscope trace of the measured energy spectrum at $V/V_0 = 0.77$. Figure 5 shows the equivalent condition PARMTEQ spectrum. The fact that the computed and measured results agreed so well suggested that it might be possible to discover the cause of the peaks by using the computer code rather than by performing experiments on the physical machine. Experimenting with a code is much easier than experimenting on a machine because it is possible to get numerical answers from regions within the RFQ that cannot be approached experimentally. Using PARMTEQ, we were able to find which particles were in which peaks and then, on subsequent runs, to follow their progress through the RFQ. We were able to observe the formation of the peaks and were guided to the following explanation.

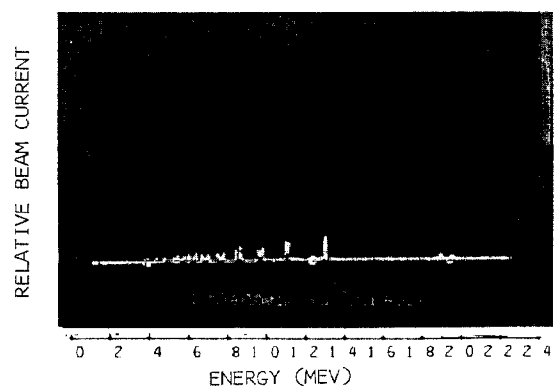

Fig. 4. Measured energy spectrum for $V/V_0 = 0.77$.

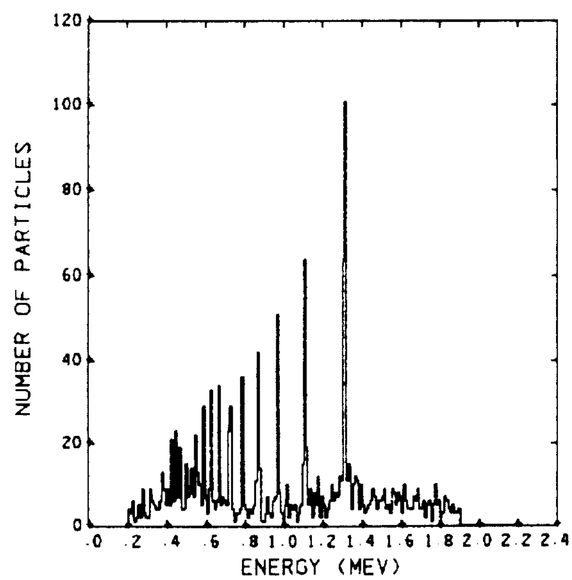

Fig. 5. Computed energy spectrum for $V/V_0 = 0.77$.

Let us consider particles that are lost from phase-stable buckets in a linear accelerator because of insufficient velocity to maintain synchronism. These particles will slip in phase relative to the synchronous particle and will follow a trajectory in longitudinal phase space that is just slightly below one of the separatrix trajectories shown in Fig. 6. After a particular number of rf periods, the particles

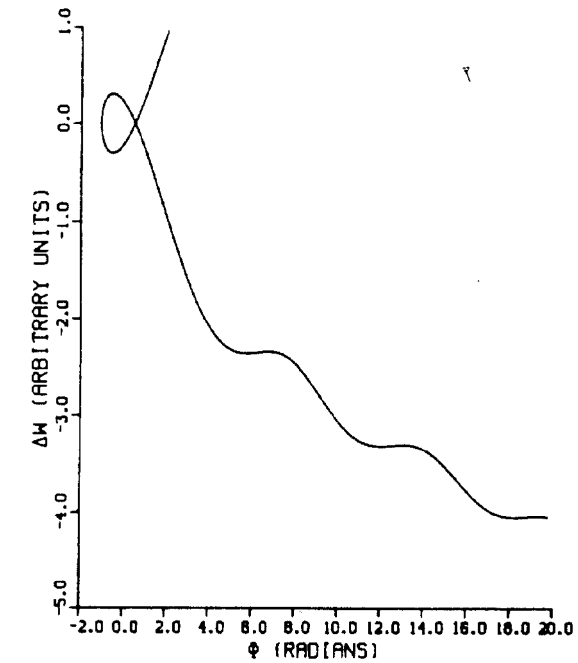

Fig. 6. Plot of the longitudinal Hamiltonian separatrix. Units are arbitrary.

will coincide with a trailing bunch and will be accelerated by the same fields that accelerate phase-stable particles. The phase-space trajectory during this time will have approximately zero slope. When the distribution is projected onto the energy axis, peaks will result that correspond to those regions of zero slope.

An accurate analytical treatment is complicated by the space-charge force and by the rapidly changing parameters in the RFQ. Nevertheless, a model that ignores the space-charge force is sufficient for purposes of illustration. If the longitudinal electric field E_0, the synchronous phase ϕ_s, and the synchronous velocity β_s all vary slowly over a longitudinal oscillation period, and if the energy difference ΔW of particles relative to the synchronous energy is small, the separatrix curve is given by

$$\frac{\Delta W}{mc^2} = \pm\sqrt{\frac{qE_0 T\lambda(\beta_s\gamma_s)^3}{\pi mc^2}}$$

$$\times\left[(\phi + \phi_s)\cos\phi_s - (\sin\phi + \sin\phi_s)\right]^{1/2},$$

where ϕ is the particle phase, mc^2 the rest energy, q the charge, T the transit-time factor, λ the rf wavelength, and $\gamma_s = (1 - \beta_s^2)^{-1/2}$. A phase-space plot of the lower branch of ΔW (the minus sign) versus ϕ for several rf cycles is shown in Fig. 6. The peaks in ΔW correspond to regions near $\phi = 2\pi n$ with n an integer.

The multiple-line-spectrum effect may be especially strong in an RFQ for two reasons. First, stable buckets are formed near the beginning of an RFQ. The phase width gradually decreases during adiabatic bunching, and this decrease causes particles to be squeezed continuously from the shrinking bucket. Second, because the electric transverse focusing is effective for particles of all energies, the lost particles generally will be transported efficiently to the exit where they can be detected.

This explanation of the energy peaks predicts that similar peaking should be present in the low-energy tail of a beam emerging from an RFQ operating at design vane voltage. In normal operation, experimental observation of the peaks is extremely difficult because the low-energy tail usually contains less than 2% of the total beam. However, it is not difficult to investigate the low-energy tail of a PARMTEQ computed beam. Figure 7 shows the energy spectrum in the low-energy tail of a beam issuing from an RFQ operating at normal vane voltage. The predicted peaking is present.

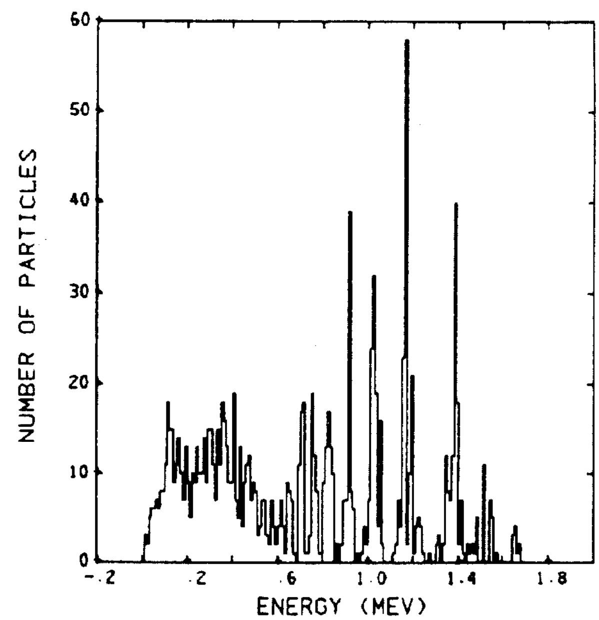

Fig. 7. Energy spectrum in the tail of a computed PARMTEQ beam. RFQ operation is at normal vane voltage. The main peak near 2 MeV is not shown.

Conclusions

PARMTEQ has proved to be very good at simulating transmission at lowered vane voltage and is able to duplicate the measured spectrum effects.

Acknowledgment

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3. P. W. Allison, J. D. Sherman, and David B. Holtkamp, "An Emittance Scanner for Intense Low-Energy Ion Beams," IEEE Trans. Nucl. Sci., 30 (4), p. 2204 (August 1983).