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EXPERIMENTAL INVESTIGATION OF RELATIONSHIP BETWEEN NONLINEAR FIELD ENERGY AND EMITTANCE GROWTH

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Final Report

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This report reviews the theory of emittance growth in a solenoidal focusing field. An experiment to validate this theory, the experimental apparatus, and results are described. This is the final report on the experiment first described in AFWL-TR-87-128.

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INTRODUCTION

Understanding the phenomena of emittance growth in space-charge-dominated particle beams is important to any application that requires a small final emittance. Many researchers have looked at the process of emittance growth under these conditions (Refs. 1-6). Wangler, et al. (Ref. 1), uses the idea of nonlinear field energy to describe emittance growth. In brief, a beam with a nonuniform radial intensity distribution has a potential energy associated with this distribution. As the beam propagates through a solenoidal magnetic field, this potential energy is turned into transverse kinetic energy and manifests itself as emittance growth.

This report is a continuation of the experiment first described in AFWL-TR-87-128 (Ref. 7). This report briefly reviews the theory and describes the experiment to check the validity of the theory. The apparatus of the experiment, the electron gun, the magnetic optic (solenoid), and emittance scanner are described in the third section. The experimental data and results are discussed in the fourth section.

THEORY

Studies by Wangler, et al., on the relationship between nonuniform radial intensity distribution and emittance growth in a space-charge-dominated transport system have recently been published (Ref. 1). These studies considered continuous beams with azimuthal symmetry and continuous linear focusing. The resulting equation relates RMS emittance and the nonlinear field energy.

$$\frac{\epsilon}{\epsilon_i} = \left[1 - \frac{(U-U_i)}{2w_0} \left(\frac{\omega_0^2}{\omega_i^2} - 1 \right) \right]^{\frac{1}{2}} \qquad (1)$$

Here ω_0 is the zero current betatron frequency, ω_i is the initial betatron frequency for an equivalent beam including space charge, w_0 is the self-electric field energy per unit length, and ϵ_i, U_i are the initial emittance and nonlinear field energy, respectively. Reiser (Ref. 5) shows that the initial betatron tune ratio, ω_i/ω_0 is given by

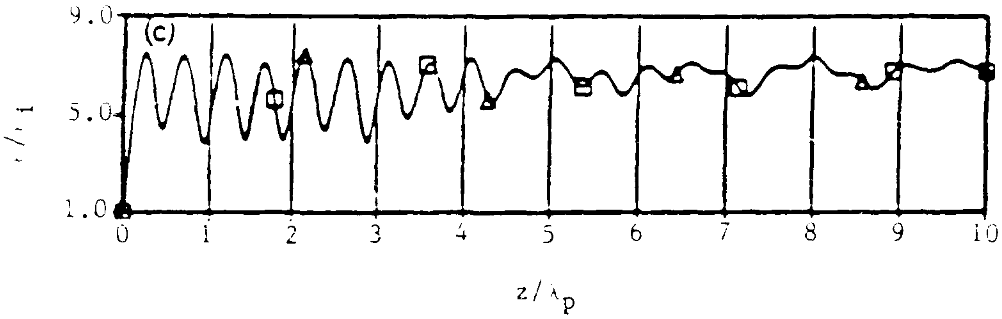
$$\frac{\omega_i}{\omega_o} = \frac{\epsilon 2 m_0 \beta\gamma}{r^2 q B_z} \qquad (2)$$

Wangler, et al., states that U/w_0 is zero for a radially uniform charge distribution and is positive both for peaked and hollow distributions. U/w_0 increases as the distribution becomes less uniform. Furthermore, U/w_0 is independent of both beam current and RMS beam size, and is only a function of the shape of the distribution (Ref. 1). Thus, if the beam distribution is flat, zero emittance growth will occur. And furthermore, the emittance growth of a beam with small initial value of U/w_0 should be less than the emittance growth of a beam with a larger initial U/w_0 if the final U/w_0, beam radius, and tune ratio are the same.

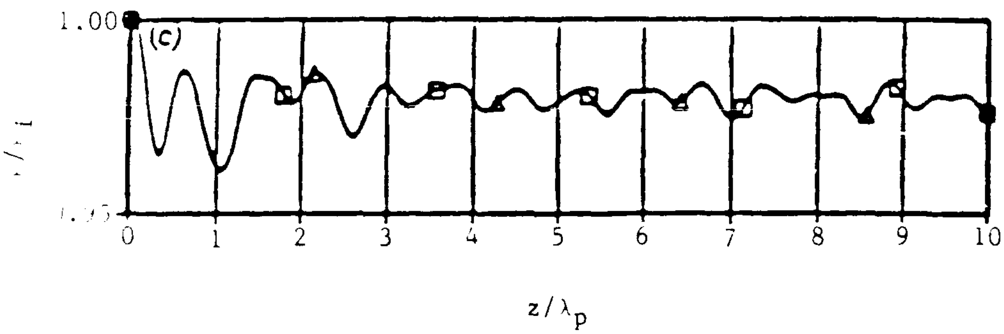
Figure 1 shows two graphs (Ref. 1) of a numerical computer simulation for an initial uniform (flat) and Gaussian (peaked) charge distributions. The triangles on the curves correspond to emittance calculations using Equation 1. The abscissa is the distance along the beamline, Z/λ_p, where λ_p is the distance the beam travels in one plasma period. For a 2-kV, 1-mA electron beam, 2.54 cm in diameter, λ_p is 4.33 m.

Wangler, et al., also shows that, as a Gaussian beam is focused, the beam distribution becomes more uniform. The U/w_0 for the beam decreases, and the emittance increases. Figure 1 reveals a large emittance ratio change of the Gaussian distribution in the first quarter of the first plasma period. The slope of the emittance ratio change for the Gaussian distribution is positive, therefore, the beam should experience an emittance increase when traversing a short solenoidal focusing field. In the numerical simulation (Ref. 1), the hard edge of the uniform beam evolved into a soft edge which resulted in an increased U/w_0 of the uniform beam and a slight emittance ratio decrease.

The emittance ratio is also dependent on the initial tune ratio. The tune ratios of the two graphs are different, but the sign of the slope of the emittance ratio is determined by the initial distribution, not the tune ratio.



(a) Initial Gaussian (peaked) distribution with an initial tune ratio of 0.02.



(b) Initial uniform (flat) distribution with an initial tune ratio of 0.25.

Figure 1. Analytical prediction of emittance growth.

EXPERIMENT DESIGN

In Equation 1, the emittance growth of a beam in a solenoidal focusing field is dependent on the shape of the charge distribution, the beam size, and the tune ratio. If the beam size and tune ratio for two different beams are held constant, then the difference of the emittance growth is a function of the distribution only. This difference in the emittance growth for the two distributions is the basis for an experiment to verify this theory.

The apparatus chosen to test this theory is a charged particle beam, for simplicity an electron beam, that can produce beam intensity profiles that have different values for U/w_0, preferably Gaussian and uniform charge distributions. This simplifies the experiment since any changes in the electron gun design, or any changes in the cathode design itself, can contribute to different variables in the emittance measurements.

In the original proposal for this experiment, the emittance of the electron beam with one charge intensity distribution is measured at the entrance of the solenoid. Next, the beam is focused with a solenoid focus coil; and, finally the emittance is measured at the exit of the solenoid. The absolute value of the emittance is not important, just the change in the emittance. The last step is to change the intensity distribution and repeat. The value of the focusing field is not changed, which holds the initial tune ratio constant. The emittance values before and after focusing will then be compared to the theory.

The actual experiment differed from the original proposed experiment. With only one emittance measurement apparatus available, the electron gun would be exposed to air when the emittance measurement device was moved from the entrance of the solenoid to the exit. The cathode used in the electron gun oxidizes when exposed to air, and would not produce a beam with exactly the same characteristics when placed back under vacuum. This factor contributed to the decision that the emittance would be measured at the exit of the solenoid only.

To avoid as many alignment problems as possible, the solenoid needed to be placed as close to the anode of the electron gun as possible. An iron plate was placed between the anode and the solenoid to shield the cathode from the solenoid's magnetic field.

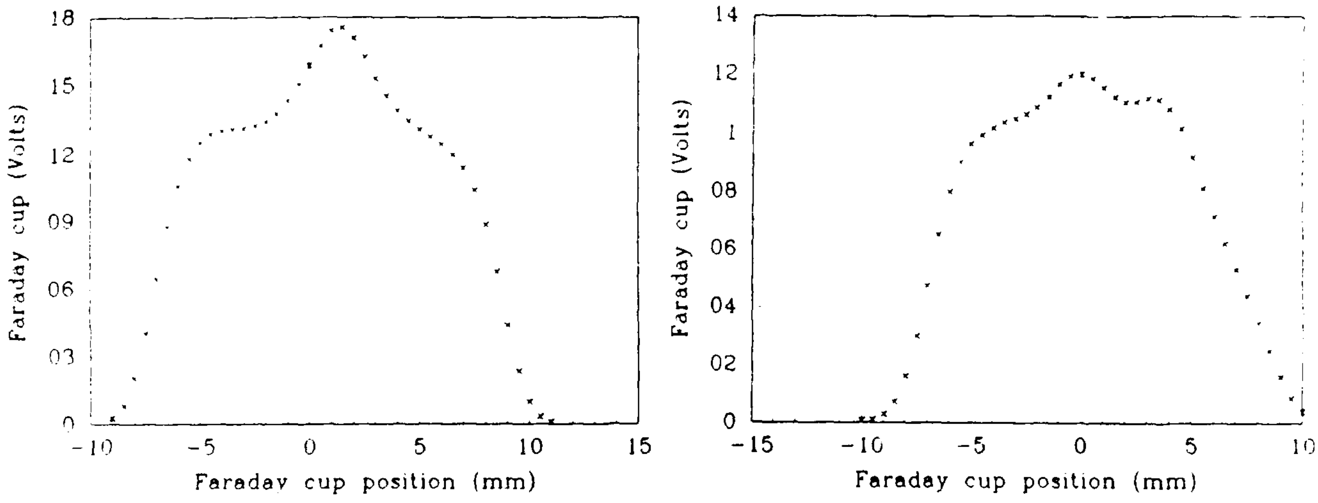
The emittance was measured at the exit of the solenoid with no focusing first, then with a focus coil current of 0.025 A and 0.050 A which produced field strengths of 26 and 44 gauss, respectively. Then the beam profile was changed and the emittance measurements for the three field values were repeated. By changing the focus field value, the tune ratio also changed. This allowed a further check of the emittance equations by adding a controlled variable.

EXPERIMENTAL APPARATUS

The main component of this proposed experiment is the electron gun. The characteristics of this gun are described in an earlier report (Ref. 7). To summarize, the electron gun is a Pierce design with a flat-plate, open-hole anode. The cathode of the electron gun is directly heated lanthanum hexaboride (LaB_6). By changing only the electrical connections to the cathode, the temperature profile across the face of the cathode can be changed.

Since LaB_6 is a thermionic emitter, the electron density is greatest where the temperature of the cathode is greatest. The "peaked" profile has a hot spot in the center of the cathode. The temperature difference between the center and edge of the cathode is on the average 70°C. This temperature difference produces the beam profile shown in Figure 2a. The temperature difference for the "flat" profile is approximately 20°C. This produces a beam profile that is more flat than the peaked profile, which is shown in Figure 2b.

The electron gun is operated at 2-kV accelerating potential and can produce 10 mA of continuous beam current. The beam profile is measured with a Faraday cup that is masked with a 1-mm-diam pinhole, 30.5 mm from the anode. The entire experimental setup is contained in a vacuum tank capable of 3×10^{-7} torr, 8×10^{-7} torr when the electron gun is operating.



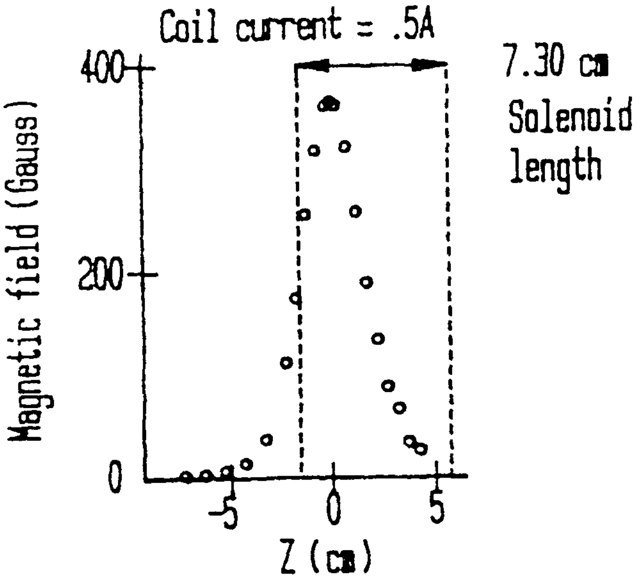
(a) Peaked profile.

(b) Flat profile.

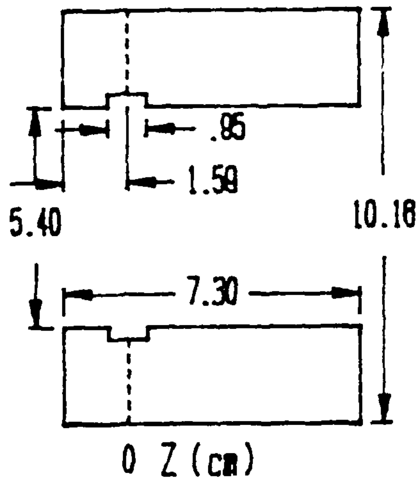
Figure 2. Electron beam profiles.

The axial magnetic field and dimensions of the solenoid focus coil used in this experiment are shown in Figure 3.

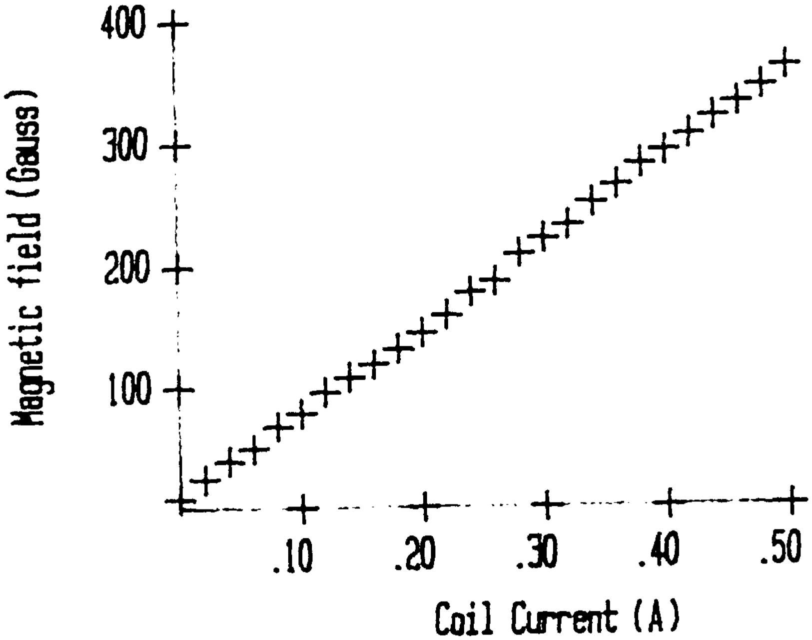
The emittance measurement device for this experiment, shown in Figure 4, uses the slit-pinhole method to measure the transverse emittance. The emittance scanner consists of four main parts: the slit, pinhole/Faraday cup, and two linear translators. The slit is made from two stainless steel wedges placed 0.75 mm apart, mounted on a linear translator that moves the slit across the face of the beam. The wedge separation is adjustable. The position of the slit is measured from a value of zero at the cathode center. The profile of the beamlet that penetrates the slit is measured by a pinhole/Faraday cup assembly. A copper plate with a 1-mm-diam pinhole is placed in front of a Faraday cup. The cup assembly is also mounted on a linear translator 180 mm behind the slit. The cup's linear translator is mounted on the slit's translator so that the position of the pinhole/Faraday cup is relative to a



(a) Axial magnetic field on the Z axis.



(b) Solenoid dimensions (cm).



(c) Field vs. coil current.

Figure 3. Solenoid lens.

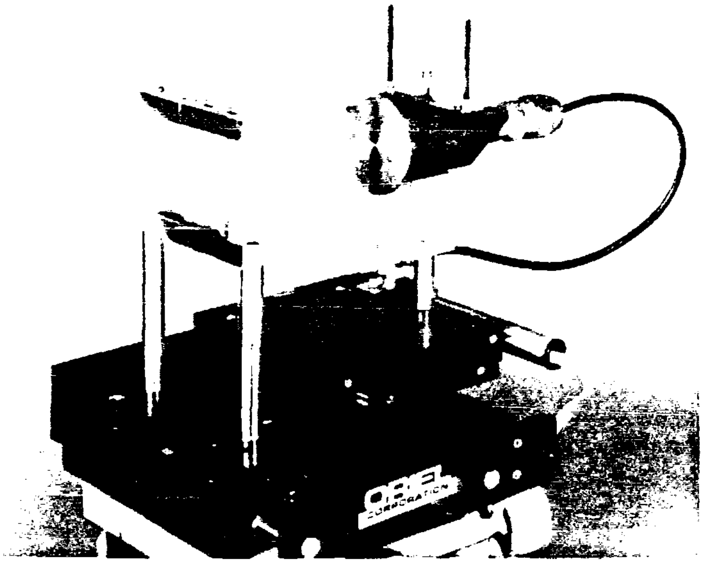


Figure 4. Slit-pinhole emittance scanner.

zero value at the slit center. A digitizing oscilloscope measures the beam current from the Faraday cup. The motor controller for the linear translators supplies the positions of the slit and pinhole/Faraday cup. A microcomputer controls both the motor operation and data collection.

The emittance is calculated by a program that reduces the raw data collected by the emittance scanner. The calculations (Ref. 8) assume that the transverse velocity distribution is Gaussian at all points across the beam profile, but the density and temperature distributions as a function of radius are arbitrary. By fitting Gaussians to the angular intensities observed at each slit position, functions for the beam intensity (beta), local transverse velocity spread (sigma), and local divergence angle (alpha) are determined. These functions are then used to calculate first and second moments of the phase space density distribution and from there, the emittance. The program provides plots of the raw data and the beta, alpha, and sigma functions.

EXPERIMENTAL RESULTS

The emittance measurements of the peaked and flat profile beams show that the emittance of the beam is increased with focusing. The amount of the emittance increase is dependent on the initial beam intensity profile and the focusing strength. The emittance of the peaked profile beam without focusing was 6.3 cm-mrad. The emittance of the peaked beam with solenoid focusing fields 26 and 44 gauss was 9.2 and 13.5 cm-mrad, respectively. The emittance ratio of focused versus unfocused beams was 1.47 and 2.14 for the respective fields of 26 and 44 gauss.

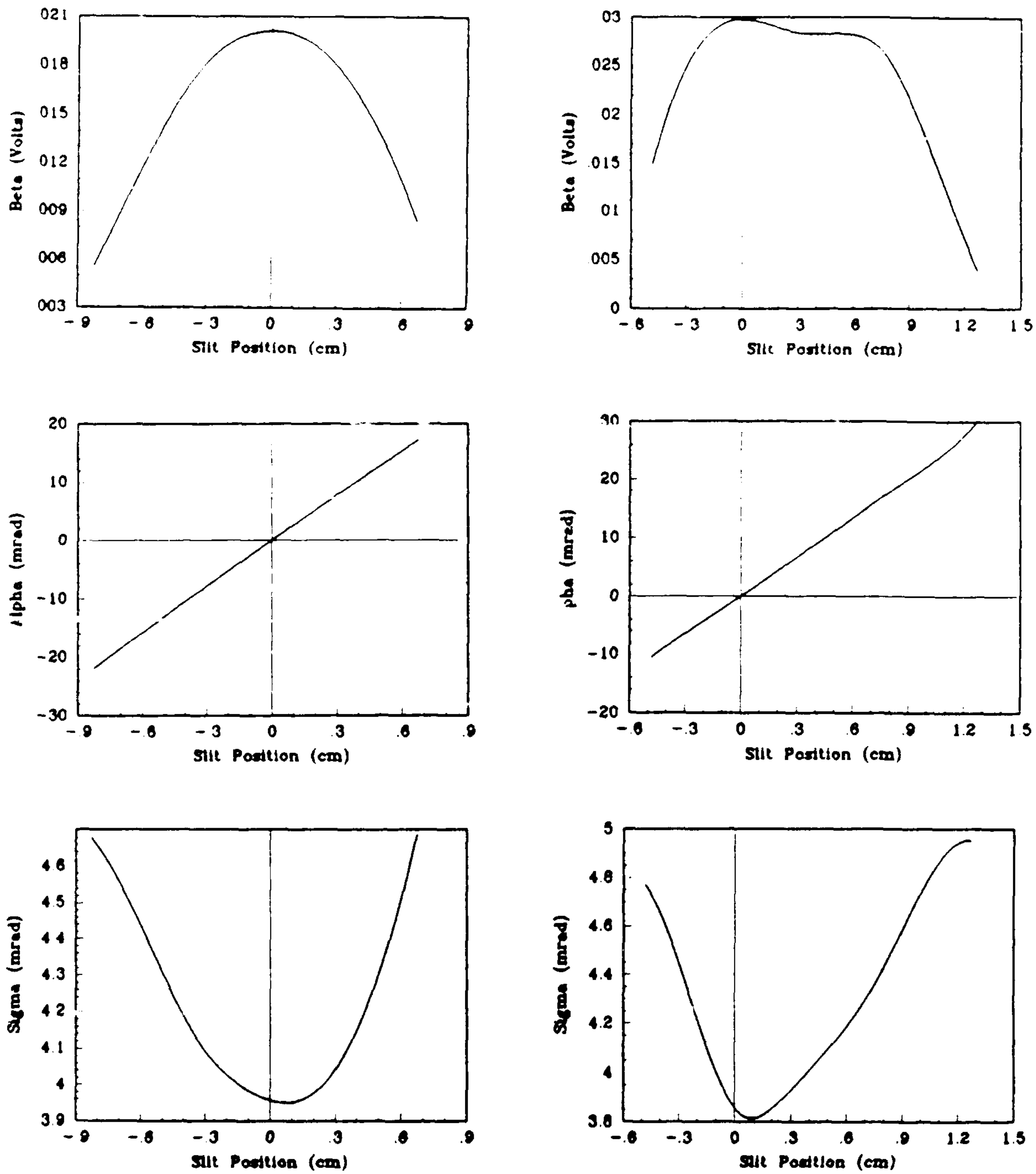
The emittance of the flat profile beam without focusing was 9.6 cm-mrad. The emittance with focusing was 11.4 and 12.7 cm-mrad for the 26 and 44 gauss fields, respectively. The emittance ratio of focused versus unfocused beams was 1.18 and 1.32 for the respective fields of 26 and 44 gauss.

The experimental results show that the emittance increase is dependent on the amount of focusing and that the ratio change for the peaked profile beam was greater than that of the flat profile beam. Figures 5 and 6 show the beta, alpha, and sigma plots for the unfocused, and 26 and 44 gauss focused beams for both the peaked and flat profile beams.

The data plots shown in Figures 5 and 6 are from 9 slit positions 0.25 cm apart across the face of the beam. The pinhole data consist of 16 data points, 0.06 cm apart centered on the slit center for each slit position. Each data run requires approximately 50 min to complete. Due to oxidation of the cathode surface, the cathode output characteristics began to change after

4 h of operation. This time window limits the amount of time available for each data run, which in turn limits the number of slit positions and data points per slit position. In some data runs, the magnitude of the slit position data on the outer edge of the beam was too small for the Gaussian fit program and contributed little to the calculation of the emittance value since they constitute a very small portion of the beam. These data points are discarded.

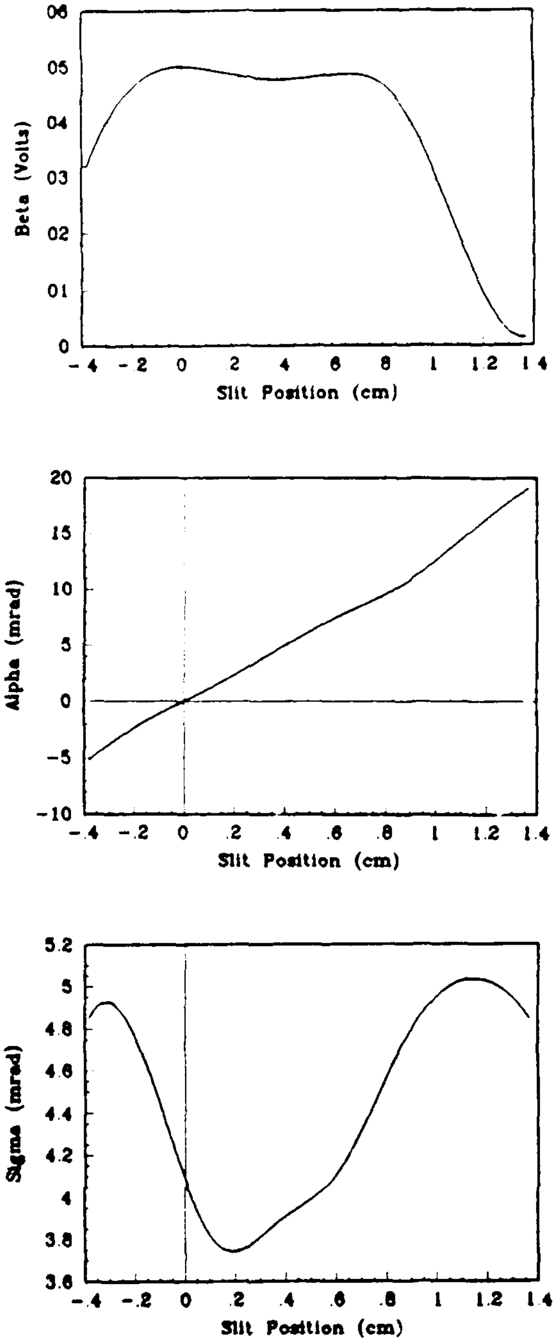
Wangler, et al. (Ref. 1), predicted that, during focusing, the intensity distribution of the initial Gaussian or peaked beam would become more uniform, while the intensity distribution of the uniform beam would become peaked. The beta plots in Figures 5 and 6 show the intensity profile for the peaked beam flattening and the profile of the flat beam becoming peaked.



(a) Unfocused beam.

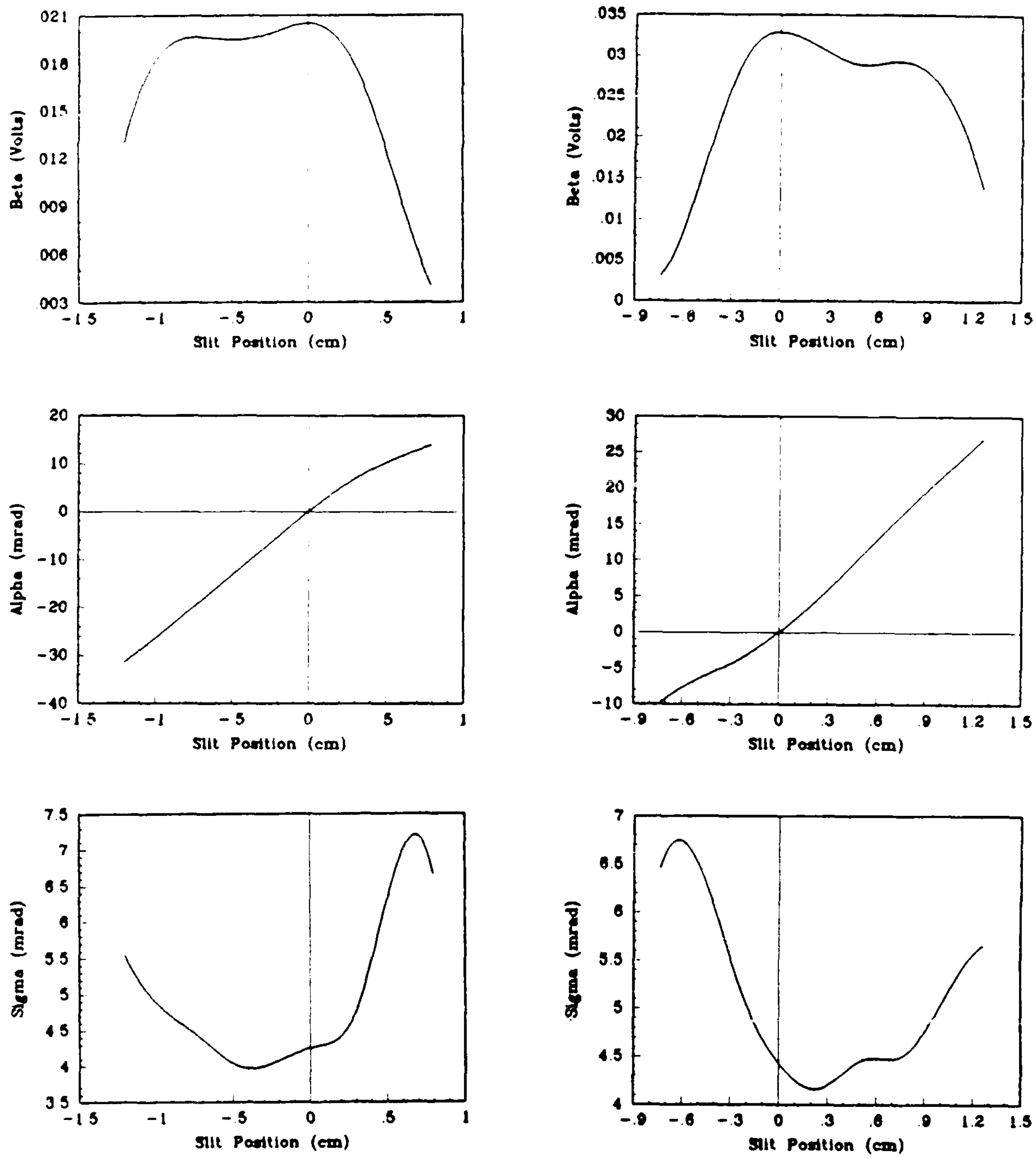
(b) Focused beam 26 gauss.

Figure 5. Emittance parameters peaked profile beam.



(c) Focused beam 44 gauss.

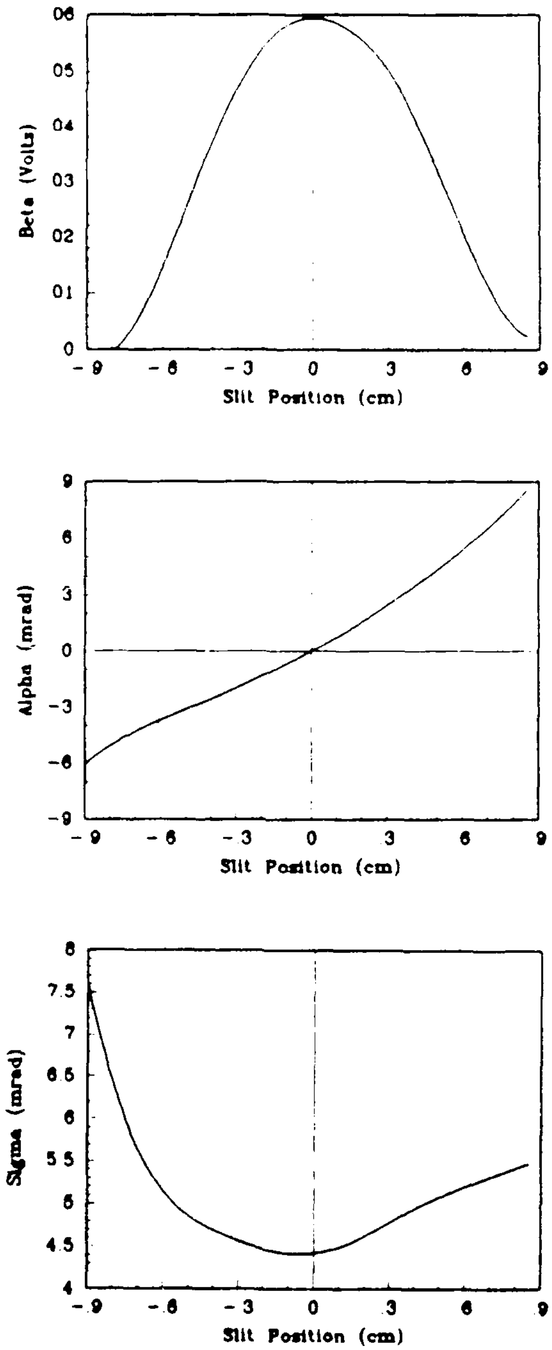
Figure 5. (Concluded).



(a) Unfocused beam

(b) Focused beam 26 gauss.

Figure 6. Emittance parameters flat profile beam.



(c) Focused beam 44 gauss.

Figure 6. (Concluded).

CONCLUSIONS

The purpose of this report is to present the theory and experimental results of an attempt to verify the relationship of the intensity profile to the emittance growth of particle beams in solenoidal focusing fields. The experimental results show that there is a relationship between the initial intensity profile and the tune ratio to the emittance of charged particle beams in solenoidal focusing fields. The results also agree with the predicted beam intensity profile changes under focusing for peaked and flat beams. This experiment shows that an experiment to verify this theory by using two different beam intensity profiles is feasible. More experimentation in this area is recommended.

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