UCID-19839

MEASUREMENTS OF THE EMITTANCE AND CURRENT DENSITY
PROFILE OF THE BEAM PRODUCED BY THE ATA INJECTOR*

UCID--19839

DE83 016522

Thomas J. Fessenden

June 27, 1983

ABSTRACT

Measurements of the normalized emittance of the beam produced by the Advanced Test Accelerator (ATA) injector yielded values near 0.4 Radian-Centimeters at currents up to 10 kAmps. The instrument was also used to obtain beam-current-density profiles in two dimensions at the entrance mask of the instrument.

* Work performed jointly under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract W-7405-ENG-48 and for the Department of Defense under Defense Advanced Research Projects Agency ARPA Order No. 4395 A#12, monitored by Naval Surface Weapons Center under document number N60921-83-WR-W0113.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

[Handwritten signature]

I. INTRODUCTION

Initial beam tests of the ATA injector began in late November 1982. One of these tests was a measurement of the intrinsic emittance of the ATA beam. The beam originates from a plasma cathode source and is accelerated by a single gap to approximately 2.5 MeV. The emittance was determined by measuring the beam current and density profile and the internal angle at which the beam electrons are spreading from the mean direction of travel. The emittance box evolved from similar systems used to measure the emittance of the Astron beam. The device was originally developed to measure the emittance of the ETA beam.

Emittance measurements (1) have recently been made on the beam generated by the FXR injector. A similar technique was used to that reported here in that the primary beam was allowed to strike a carbon mask containing many small holes. The beamlets then excited a phosphor creating an image that was recorded with a photographic camera. The image was then analyzed to obtain beam emittance. Typical normalized values of beam emittance of 90 to 120 mr-cm were obtained at beam currents of 1-3 kA at an energy of 1 MeV.

II. EMITTANCE BOX DESCRIPTION AND DESIGN CONSIDERATIONS

The ATA beam emittance at the injector output was measured by the technique shown schematically in Fig. 1. The beam is allowed to impinge on a range thick carbon mask at a typical radius of 5 cm. The mask contains approximately 250 vertical and horizontal slots which divide the primary beam

into a corresponding number of beamlets. The mask slot pattern shown in Fig. 2 was chosen to facilitate the alignment of the TV axis to the slot axis and to simplify the fabrication of the mask. The beamlets pass through a drift region of approximately 23 cm in which they freely expand. They then pass through a range thin aluminum foil and excite a fast phosphor deposited on the foil back. Using front surface mirrors the image created by the beamlets is relayed to a gated TV/computer system which records and analyzes the image.

A sketch of the optics containing a definition of the angles and lengths is given in Fig. 3. In this schematic the maximum angle that can pass through the slot is shown. The instrument is only useful if the measured width is considerably less than $2W$. For this instrument the slots have a width of 0.051 cm and the carbon is 1.27 cm thick. The slot acceptance angle θ_k is 0.04 radians and W equals 0.92 cm. This places a limit on the maximum normalized emittance that can be measured by this instrument $(\theta_k r_b \gamma / 2)$ of approximately 0.6 for the parameters of this experiment. The slots are located 1.35 cm apart. As a consequence, if the beam emittance is too large to be measured with this instrument, the images of the slots at the phosphor plane overlap.

The TV image is generated by the electrons passing through a cadmium doped ZnS phosphor deposited on the back of a 0.025 cm aluminum sheet. The phosphor has a time decay of less than one nanosecond. Four holes located symmetrically on a 3 cm radius circle about a center hole are used to determine size in the TV image.

The TV system uses a micro-channel-plate intensifier in front of a charge coupled silicon chip as the optical detector. On command the image is "grabbed" electronically and digitized for storage and later analysis by a microprocessor. The camera is capable of obtaining a picture in approximately 3.5 nsec. In these experiments a 10 nsec gate pulse was used.

Through the use of shielding, the peak magnetic field inside the emittance box produced by the magnets of the beam transport section was reduced to less than 10 gauss. At 10 gauss and 2.5 MeV the beamlet can be expected to deflect at most a few millimeters between the mask and phosphor causing very little defocussing.

Space charge tends to spread beamlets and must be considered. Initially, the beamlet current density is equal to that of the primary beam. The beamlets are rectangular and the narrow dimension is most important. A simple derivation of the force experienced by each beamlet is given in Appendix A. This force will cause a transverse beam spreading δx over the drift length L within the emittance box given by

$$\frac{\delta x}{x_0} \approx 2i (L/av)^2 \quad (1)$$

Here x_0 is the initial half width of the beamlet, a is the beam radius, and i is the beam current normalized to the Alfven current. This relation is only valid if the spread δx is small compared to beamlet width x_0 .

For the parameters of this experiment we find $\frac{\delta x}{x_0} < .15$ at 10 kA, 2.5 MeV, 5 cm radius. As a consequence, at maximum parameters beamlet spreading due to space charge will contribute no more than 15% to the emittance measurements.

A focusing force (2) is generated as a high current beam strikes a conducting plot. The force arises because the radial electric field around the beam is shorted near the plate but the transverse self magnetic field is unchanged. An estimate of this effect shows that initially parallel beam electrons are deflected toward the axis by the angle approximately given by

$$\theta = \frac{r}{Z} \approx -2 \frac{r}{R^2} \quad (2)$$

Here R is the radius of the beam drift tube and r is the radial electron position. This force acts coherently on the beam electrons in a way similar to that impressed on the beam by the magnetic focussing system.

The above discussion assumes that the mean direction of the electrons in the primary beam is parallel to the accelerator axis. In general the primary beam will be converging or diverging inside the emittance box as determined by the beam transport system. A diverging beam appears in emittance space as a positive rotation of the major axis of the emittance ellipse into the first and third quadrants. The major ellipse axis of a converging beam falls into the second and fourth quadrants of emittance space. This angular rotation can be obtained from the TV beamlet image by comparing the beamlet spacing measured with the TV system with the known slot spacing in the mask. A little geometry reveals that the rotation angle θ_r is given by

$$\theta_r = \tan^{-1} \left(\frac{P-S}{L} \right) \quad (3)$$

where P is the spacing at the phosphor surface and S is the slot spacing at the mask.

If the beam is strongly converging or diverging, the slot in the mask can apperture the beamlets unsymmetrically leading to a better-than-actual emittance determination. To avoid this error the beam expansion angle plus the rotation angle θ_r must be less than the slot acceptance angle θ_k .

III. EXPERIMENTAL RESULTS

ATA emittance measurements were made beginning December 3, 1982 and terminating January 24, 1983. Initial results are shown in Fig. 4. Here the angular divergence was obtained using the Computer Scan System as shown in Fig. 1. However, the beam size was only crudely estimated from the TV image as also shown in Fig. 1.

In January the computer was used to estimate the beam size as well and thereby remove some of the subjective interpretation from the data. The digitized TV image was normalized so that the brightest pixel had a value of 255. Then the calibration marks on the phosphor were used to inform the computer of the scale size of the TV image. Next the computer estimated the beam size by finding the rectangular area containing pixels of value greater than 128. The largest rectangular dimension was used as the diameter of the beam for the emittance calculations.

Figure 5 shows normalized emittance measurements of the ATA beam at an energy of 2.5 MeV at currents varying between 6.0 and 10 kiloamps. Each point represents from 20 to 40 individual emittance measurements obtained with the emittance box technique described above. Shown are the mean of the data and one standard deviation. For most of these experiments a coarse grid (80% transmission, 1 cm mesh) was used in front of the ATA plasma cathode. These

data are plotted with a rectangular dot. Near the end of the experiments a fine grid (60% transmission, 0.15 cm mesh) was used. Data taken with a fine grid are plotted with a circular dot.

A study of beam emittance variation with bucking coil current is presented in Fig. 6. These data were taken at 2.5 MeV at a beam current of 7 kAmps.

During these experiments attempts were made to measure the beam emittance versus time in the pulse by varying the TV gate over the beam pulse. In each case no significant changes of emittance above statistical variations could be detected.

The emittance box system was also used to produce beam profile measurements. The slot mask was replaced with a pinhole mask consisting of one millimeter pinholes located 5 millimeters apart. The pinhole mask attenuated the beam thereby preventing damage to the phosphor. These pinholes were so close that the beamlets they produced overlapped at the plane of the phosphor. Consequently, the image generated by the phosphor could be used to obtain the relative beam current density in two dimensions.

Figure 7 shows a "3d" plot of the beam current density at the plane of the phosphor. This data was obtained at an energy of 2.5 MeV and a beam current of 7.5 kAmps. The transport was carefully adjusted to focus the beam to as small a size as possible. Using the radius of the beam pipe and the distance from the last transport magnet to the emittance box mask we can obtain an upper bound of the normalized beam emittance of .7 rad-cm based on the measured size of the beam at the plane of the phosphor.

IV. COMMENTS AND CONCLUSIONS

Although the beam current measured in front of the emittance box was very repeatable, these measurements were troubled by a lack of reproducibility on a microscopic basis. The beam was not uniform as is shown in Fig. 7 and the beam microstructure was repeatable on a pulse-to-pulse basis in only a general sense. For this reason the more detailed and precise reduction of the data that would yield a true phase plane plot of the beam emittance was not possible. Nonetheless, the emittance measured in these experiments is quite close to that expected. Theory (3) predicts that the fields near the grid should generate a normalized emittance near 0.3 radian centimeters at beam currents considerably below the virtual cathode limit. The data of Fig. 5 suggest a normalized beam emittance of .4 to .5 rad-cm which is near the predicted value. However, the factor of six change in wire mesh spacing during these experiments should have produced a corresponding change in the beam emittance. Consequently, the factors causing the lack of microscopic repeatability are probably contributing more to the beam emittance than effects due to the grid wires.

Art Paul has calculated (4) that as the current approaches the virtual cathode limit, the emittance fluctuates then increases rapidly to very large values as the limit is reached. The data of Fig. 5 supports this dependence although the large statistical error makes quantitative conclusions impossible.

Figure 6 shows that the field produced by the bucking coil has little to no effect on the emittance as measured by this technique. The purpose of the bucking coil is to cancel the fields produced by the gun anode magnets thereby

reducing the canonical angular momentum of the beam to near zero. If this is not done, the beam spins as it leaves the fields of the magnetic transport system resulting in a large and diverging beam in the emittance box. However, this motion is ordered and does not cause as an increase in the incoherent beam divergence angle. As shown in Fig. 7, the principle result of adjusting the bucking coil currents is to produce a small beam spot. This small spot required a careful tweaking of both bucking coils.

APPENDIX A

1. Beamlet Spreading due to Space Charge

The rectangular beamlets are formed by the primary beam shielding the mask. Thus, the beamlets have the same current density as the primary beam. Consequently, the transverse electric field E_x tending to spread the beamlet is given by

$$E_x = \frac{J_b x}{\beta c \epsilon_0} \quad (4)$$

Here x is the transverse coordinate measured from the center of the beamlet and ϵ_0 is the permittivity of free space. Similarly, the beamlet current generates a transverse magnetic field

$$B_y = \mu_0 J x \quad (5)$$

From the Lorentz equation the net force experienced by an electron is this

$$F_x = \frac{J_b x}{\beta c \epsilon_0 \gamma^2} \quad (6)$$

This motion equation for an electron within the beamlet located x meters from the beamlet axis is

$$\gamma mc^2 \frac{d^2 x}{dz^2} = \frac{J_b x}{\beta c \epsilon_0 \gamma^2} \quad (7)$$

Let us anticipate small motion and set

$$x = x_0 + \delta x; \quad \delta x \ll x_0 \quad (8)$$

We then find

$$\frac{\delta x}{x_0} = \frac{2I}{I_a} \left(\frac{z}{ay} \right)^2 \quad (9)$$

Where a is the radius of the beam striking the mask and I_a is the Alfven current 17 BykA. The spreading of the beamlet is found once we identify x_0 as the half width of the slot and Z as the drift length in the emittance box.

The above analysis does not consider the fields produced by neighboring beamlets on the test beamlet. Note that these fields will tend to act equally on all the electrons in the test beamlet and will tend to cause the entire bundle to diverge. This can lead to an error in the determination of the radius of the beam on the phosphor plate. However, this error is smaller than the above by approximately the ratio of total current passing the emittance mask to the beam current.

REFERENCES

1. B. Kulke and R. Kihara, "Emittance Measurements of Field Emitter Diodes," LLNL UCRL 82533 (April 5, 1979).
2. R. J. Adler, "Image Field Focusing by Intense Ultrarelativistic Electron Beams in Vacuum," Particle Accelerators 12, 39-44 (1982).
3. J. R. Pierce, Theory and Design of Electron Beams, p. 96, Van Nostrand & Co., NY (1954).
4. T. J. Fessenden, et al., "Physics of a Repetively Pulsed 10 kAmp Electron Beam Accelerator." Presented at 4th Int'l Topical Conference on High Power Electron & Ion Beam Research & Technology, Palaiseau, France (1981).

TJF/kaw

ATA EMITTANCE MEASUREMENT

TV image

Normalized
emittance ϵ

$$\epsilon_n \approx \gamma \times \text{radius} \times \text{half angle}$$

Beamlet pattern and computer image scan

$I_b = 7.5 \text{ KA}$ $E_b = 2.5 \text{ MeV}$ $\epsilon_n = 0.4 \text{ radium cm}$
10 nsec gate

Fig. 1

Fig. 2. Details of the emittance box mask

Fig. 3. Sketch of the beamlet geometry

Fig. 4. Results of initial emittance measurements

Fig. 5. Beam emittance measurements at 2.5 MeV. Each point represents approximately 25 determinations. Error bars are at one standard deviation.

Fig. 6. Beam emittance versus bucking coil current. Each point represents approximately 25 determinations. Error bars are at one standard deviation.

Fig. 7. Three dimensional plot of beam current density profile measured at the emittance box plane. Each division is one centimeter.