HIGH BRIGHTNESS CATHODE EXPERIMENTS ON THE
EXPERIMENTAL TEST ACCELERATOR (ETA)

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SECTION 1

INTRODUCTION

The experiments performed on the ETA during the months of September through October of 1984 were intended to accomplish two objectives; to discover or develop a source capable of producing an electron beam whose brightness is substantially higher than that of previous sources, and to determine, if possible, the mechanisms which limit the source brightness so that further enhancements might be obtained. The results of the experiments met these objectives to a limited degree. A cathode material (velvet) and a diode geometry were identified which resulted in more than a factor of two improvement in brightness over that obtained with previous flashboard cathodes (see Appendix A). Experiments were performed which have yielded information about mechanisms which may limit beam brightness, and have suggested approaches for further work to improve brightness. However, the desired brightness of $10^5 \text{ A}/(\text{cm}^2\text{-rad}^2)$ was not achieved in these experiments.

This report contains a discussion of the cathodes used, the diode geometries employed, the diagnostics, the typical characteristics of a single beam experiment, and the characteristics of the collimator used to measure the brightness. The entire ensemble of brightness data is presented and broken down into classes of experiments. In addition, the results of an EBQ calculation of one diode geometry are discussed, and differences between the results of similar experiments on ETA and ATA are noted. Finally, conclusions and recommendations are presented.

SECTION 2

CATHODES

2.1 Introduction

A number of different cathodes were used in the experiments. All of the cathodes provided a plasma source of electrons as a result of the application of the anode-cathode electric field which also accelerated the electrons and formed the beam. As a result, the electron source, electron kinetic energy, and beam optics could not be independently controlled in the experiments. In most cases, the beam current was clearly space charge limited. In some cases, the current was limited by the amount or area of the plasma formed, but was probably still locally space charge limited. In either event, the beam current was dependent on the anode-cathode voltage. Since all of the cathodes had a nominal emitting area of 100 cm^2 the beam current was not varied except in conjunction with the accelerating field.

The plasma formation mechanisms differed, depending on the type of cathode. For the conducting cathodes (carbon fibers), the plasma is believed to form as the result of the explosion of microscopic whiskers that are ohmically heated by field emission currents. Although whisker material is ionized in the explosions, the most important ion species is hydrogen originating from surface contamination. For the nonconducting cathodes (velvet), the plasma formation mechanism is probably surface breakdown. Measurements on cathodes which have been used as beam sources show that they remain nonconducting, that is, they are not carbonized or converted into conducting fibers by use. Of course, the plasma is conducting during the beam pulse. The dominant plasma species is not known at this time.

Most of the experiments were conducted with velvet cathodes. The use of velvet was suggested by Richard Adler of MRC¹ who supplied some of the velvet samples which were used in the experiments. Attention was concentrated on these cathodes because of the superior brightness measured with them which was not matched by any of the other cathodes. A dielectric filled metal cathode was also constructed.

Several conducting cathodes were tested. Most were woven with carbon fibers forming a matrix of tufts. A stabbed metal cathode was also made.

2.2 Nonconducting Cathodes

The velvet cathodes were constructed by gluing the velvet to aluminum or copper substrates with a silver based conductive epoxy. Aluminum substrates were used for all of the flat cathodes; copper was used for the shaped cathodes. Good performance was obtained with both substrates and no attempt was made to study the effects, if any, of substrate material. Three sources of velvet were used: samples supplied by MRC, material purchased at a fabric store in Livermore, and material purchased in San Francisco. The MRC and Livermore velvet were composed of a rayon and cotton mixture. One of the San Francisco materials was rayon and cotton, the other was only cotton. Electron micrographs of the MRC velvet showed a randomly oriented matrix of fibers² whose diameter was approximately 6 microns with a density of approximately 10^4 ends/cm². Use as a cathode did not significantly change the density of fibers but did straighten them so that the fibers were more perpendicular to the substrate. The Livermore velvet had a similar density, but the fibers did not appear to straighten as much as the MRC velvet. The San Francisco velvets were purchased because they appeared to be significantly more dense to the naked eye. However, electron micrographs showed that they also had a density of about 10^4 ends/cm².

The performance of the velvet cathodes, together with the supposition that the flashboard cathode performance might be limited by the relatively small area of dielectric subjected to flashover, led to the construction of a dielectric-loaded metal cathode. A series of grooves was machined in an aluminum substrate and filled with epoxy. Although the applied field strengths were estimated to be marginal, it was hoped that sufficient field enhancement would be obtained at the edge of the grooves to cause local flashover of the dielectric surface. Unfortunately, the fields were not large enough and little emission was obtained from this cathode.

2.3 Conducting Cathodes

Most of the conducting cathodes employed arrays of carbon fibers. The cathodes were constructed by weaving a carbon yarn through an array of holes, and trimming the yarn by hand to form the most uniform surface of fiber ends possible. The carbon yarn was composed of approximately 1000 eight micron diameter fibers. Two array spacings were used. The "sparse" cathodes used one strand of yarn on 0.1 inch centers. The "dense" cathodes used five strands on 0.05 inch centers. Electron micrographs of the dense cathode showed a fiber density of 10^5 ends/cm² which is only a third of what should have been obtained using the manufacturer's count of the number of fibers/strand. The sparse cathodes were constructed with both flat and convex substrates. The fibers were attached to the substrate by immersing the woven substrate in molten solder. In spite of the care taken in assembly and trimming, the exposed ends of the fibers did not form a smooth surface on the finished cathode.

One cathode was constructed by stabbing a 0.01 inch thick stainless steel plate with a 0.05 inch diameter common nail. This resulted in an array of clusters of four sharp points protruding approximately 0.05 inches above the cathode surface on

1 cm centers. This cathode did not produce a beam of sufficient brightness to measure.

All of the cathodes had the same diameter and produced an area of 100 cm^2 projected onto a flat surface. All of the cathodes were mounted on the same shroud in the ETA injector.

SECTION 3

DIODE GEOMETRIES

All of the experiments employed a common set of hardware which defined the overall diode geometry. The cathode stalk of ETA was modified to produce a nearly planar surface with provisions for mounting replaceable cathode assemblies. An insert was constructed for the anode stalk which reduced the anode bore, shortened the anode-cathode gap, and permitted adjustment of the gap. The resulting gun geometry is shown in Figure 1, together with a plot of the potential distribution for this geometry. The different diode geometries used in the experiments utilized different cathode shapes and configurations with different anode-cathode spacings.

The cathode shapes included flat plates (Fig. 1), convex or domed surfaces (Fig. 2), and concave or dished surfaces (Fig. 3). The configurations included a "Pierce correction" electrode surrounding a flat cathode, and flat cathodes whose surface was setback from the non-emitting planar surface of the cathode shroud (Fig. 4). Convex cathodes which extended 0.5 and 1.0 cm beyond the 100 cm² planar cathode back were tested with the cathode back nominally aligned flush with the cathode shroud. A concave cathode recessed 1.0 cm from the 100 cm² projected planar face was also tested. Flat cathodes aligned flush with the cathode shroud were tested as well as flat cathodes set back 1/8" and 1/4" from the shroud.

Anode-cathode spacings were measured from the planar surface of the cathode shroud to the closest face of the anode insert, and are obviously not the same as the equivalent anode-cathode spacing in a plane parallel diode. Spacings of 10, 12, 14, and 16 cm were used. However, not all of these spacings were used with each of the cathodes.

30.0

Figure 1 Standard diode geometry for beam brightness experiments. Area of flat cathode aligned flush with cathode shroud is 100 cm^2 . Anode-cathode spacing is 12 cm measured from anode insert to cathode shroud.

30.0

Figure 2 Diode geometry for convex (or dome) cathode.

30 0

Figure 3 Diode geometry for concave (or dish) cathode.

30.0

Figure 4 Diode geometry for flat cathode set back from cathode shroud.

A flat cathode, aligned flush with the cathode shroud at an anode-cathode spacing of 12 cm, was considered to be the standard geometry. A number of different cathode materials were tested and retested in this geometry.

Electric fields were calculated for each of these diode geometries with the EBQ computer code. Although the potential distribution was calculated throughout the diode region, the fields were calculated only at the cathode surface on the symmetry axis. The beam space charge was not included in these calculations. The resulting field strengths indicate the relative peak electric stresses developed at the cathode surface before the cathode "lights up".

The peak electric field which could be developed on the cathode surface under the standard conditions (flat, 12 cm) is 190 kV/cm. At 10 cm anode-cathode spacing a peak field of 225 kV/cm could result for a flat cathode. The highest fields are obtained with the convex cathodes and are 275 kV/cm at 12 cm anode-cathode spacing and 315 kV/cm at 10 cm.

SECTION 4

DIAGNOSTICS

The most important diagnostic in the experiments was the collimator which was used to infer the brightness of the beam. It is discussed in a separate section below.

The electron energy was inferred by measuring the diode voltage and applying a correction factor of 1.25 as standardly used to normalize the output of this diagnostic to measurements of electron energy obtained with a magnetic analyzer. The diode voltage recorded is the electrically summed output of 20 capacitive voltage monitors located at the outputs of 1/2 of the Blumlein pulse forming lines which drive the gun. There is concern about how faithfully the output of the summer represents the true accelerating voltage applied to the diode.

The cathode shroud was provided with a resistive current monitor located near the base of the shroud. Unfortunately this monitor also passes the "displacement" current required to charge the capacitance which shunts the anode-cathode gap. This current is sufficiently large that it obscures the beam current signal. Attempts to subtract this component of the current from the total current measured in order to infer the beam current were only moderately successful, and the accuracy of these measurements is questionable. This was the only total beam current diagnostic available for the early experiments.

During the later experiments, a resistive monitor was used which was the same diameter as the cathode and was installed directly behind the cathode. This monitor provided an accurate measure of the current extracted from the cathode itself. Attempts to infer how much current might be emitted from the cathode shroud by subtracting this signal from the corrected

shroud current failed. The cathode current frequently exceeded the corrected shroud current.

A standard resistive "beam bug" was located at the output of the ETA gun. This current monitor was rarely used once the cathode monitor was installed. Additional beam bugs were located at the input and exit of the collimator, and are referred to as BB1 and BB2, respectively, in the following discussion.

Analogue signals were digitized and stored by a data acquisition system. Analysis was performed "off line" with a standard computer program supplied by LLNL.

Considerable effort was made to synchronize the timings of the different diagnostic signals so that the superimposed fiducial markers can be used to determine the relative timings of the individual signals.

A viewing port, located approximately 40 cm upstream of the entrance to the collimator, was equipped with a Kapton foil converter and a gated television camera to measure beam current density profiles. Video information was recorded on tape for post-processing with an "off line" computer system. There was no "on line" monitor for video level. As a result, most of this data was lost due to saturation of the intensifier portion of the camera.

SECTION 5

TYPICAL BEAM CHARACTERISTICS

5.1 Voltage and Current

Typical voltage waveforms are shown in Figure 5. Unfortunately they do not possess a flat top which complicates the interpretation of the data. The currents measured by the cathode monitor are shown in Figure 6. The currents are consistent with unipolar, relativistic, space charge limited current flow. The current transmitted through the collimator (measured by BB2) is shown in Figure 7. The timing markers indicate that maximum current transmission occurs 5-10 ns prior to the maximum of the measured voltage signal. Simple circuit calculations indicate that the maximum current transmitted through the collimator may very well occur at the maximum electron energy, since the voltage across the anode-cathode gap differs in shape from the measured voltage due to the finite inductance of the anode and cathode stalks and the finite shunting capacitance of the gap. These simulations show little difference between the peak accelerating voltage and the peak measured voltage. Motion of the beam across the entrance to the collimator could also account for the shortened transmitted current pulse. Intentionally inducing an average transverse displacement of the beam which was comparable to the measured temporal sweep, reduced the transmitted current by a factor of three.

The dependence of peak current on peak voltage measured at two locations is shown in Figure 8. The dependence of the current extracted from the cathode upon voltage is consistent with relativistic, space charge limited current flow. The 1.3 power dependence (rather than 1.5) is due to relativistic effects. The voltage dependence of the current at the entrance to the collimator is stronger. This is presumably due to changes in the

VOLTAGE SCAN, FLAT VELVET CATH. 920004.E FRAME: 5
 11-OCT-84 FC/10/16/84
 SCOPE NO: 1 SIGNAL NAME(1): V-ANODE FULL SCALE VOLTAGE = 1.8506E+00

Figure 5 Typical voltage waveforms for standard conditions.
 Diode voltage changed between groups of four traces.
 Full scale is 8.9 MV.

VOLTAGE SCAN, FLAT VELVET CATH. 920004.E FRAME: 9
 11-OCT-84 FC/10/16/84
 SCOPE NO: 5 SIGNAL NAME(1): I-16N170 FULL SCALE VOLTAGE - 6.4541E-01

Figure 6 Typical current waveforms corresponding to Figure 5. Full scale is 12.9 kA.

VOLTAGE SCAN, FLAT VELVET CATH. 328804.E FRAME: 7
 11-OCT-84 FC/18/16/84
 SCOPE NO: 3 SIGNAL NAME111: BB2 FULL SCALE VOLTAGE * 1.0943E-01

Figure 7 Typical current waveforms for current transmitted through collimator (BB2). Full scale is 440 A.

Figure 8 Dependence of peak cathode current and current delivered to the entrance to the collimator (BB1) on measured peak diode voltage. The 1.3 power scaling for cathode current is consistent with unipolar, relativistic, space charge limited flow.

electron optics of the diode which influence the amount of current that is extracted from the gun, but no model is proposed to explain the observed dependence.

The brightness of the electron beam was calculated from digitized waveforms by an "off line" computer program. A sample of the output of this program is shown in Figure 9.

5.2 Bucking Coil Scans

The electron beam in ETA is immersed in an axial magnetic field for extraction from the gun. Since the brightness of the beam is degraded if the beam is formed in a magnetic field, the gun is provided with a magnetic field coil located behind the cathode which is used to cancel the extraction field at the cathode surface. This cancellation can be achieved only in an average sense because the emitting plasma surface is neither perfectly flat nor stationary even if formed from a cathode with a flat substrate. For shaped surfaces, this simple "bucking" coil cannot produce cancellation even if the details of the plasma formation are ignored. In order to determine the best average cancellation of the extraction field, the beam brightness is measured as a function of the bucking coil strength (current), and the value of the coil current which maximized the brightness was then used in subsequent measurements. This tuning procedure was repeated each time machine parameters were changed, either intentionally (e.g. cathode change) or unintentionally (e.g. hardware problem).

The results of a bucking coil scan are shown in Figure 9. Multiple passes through the available range of current were made, so that the scatter of the data in this figure also indicates the short term reproducibility of the beam. All of the cathodes, including the shaped ones, exhibited a behavior similar to that shown, and no attempt was made to infer beam properties from the shape of these plots.

FLAT VELVET CATH. + CATH. SHUNT

S20003.E FRAME: 1
11-OCT-84 FC/10/12/84

BRIGHTNS:

BEAM GAUM = 5.7000E+00
BEAM BETA = 9.8419E-01
B COLLIMATOR (GAUSS) = 7.5000E+02
K CYCLOTRON (CU-1) = 7.8743E-02
L CYCLOTRON (CU) = 1.5780E+01
PIPE DIAM (IN) = 6.2500E-01
PIPE RAD (CU) = 7.9575E-01
F22SCALE (GAUSS/AMP) = 0.
SCALEB2 = 1.0000E+00

FILES:

S20001.E
S20002.E
S20003.E

Figure 9 Dependence of beam brightness (upper right) on bucking coil current. Best cancellation of transport magnetic field is obtained at about 5 Amps. Conditions same as for Figures 5-8.

5.3 Voltage Scans

All of the cathodes and diode geometries tested, with the exception of the last experiment, exhibited a very strong dependence of beam brightness on the accelerating voltage as illustrated in Figure 10. The value of the brightness presented is as calculated by the data analysis program. The voltage is the peak measured voltage. The voltage was varied by two techniques, "dropping cores" and reducing the pulsed power charging voltage. Both techniques produce similar results as shown.

"Dropping cores" refers to the practice of lowering the voltage applied to the accelerating gap by simply not charging selected pairs of pulse forming lines whose output is summed in ETA using ferrite cores. Except for some minor transit time considerations, the electronically summed voltage monitor should still measure the total applied voltage since it includes signals at the outputs of the uncharged lines. This technique was initially expected to be the easiest method for varying voltage, since the timing and switching characteristics of the charged lines would not be altered. Concerns about the legitimacy of this technique and the voltage measurement led to an attempt to achieve the same result by varying the charge voltage and using all of the pulse forming lines. This technique turned out to be relatively simple to accomplish and became the standard method for varying the accelerating voltage.

Changing the accelerating voltage caused profound changes in the current transmitted through the collimator. As a result, the entire transport system was retuned following each voltage change. This retuning process is described in the following section.

The last experiment performed followed a major change in the pulsed power system driving ETA. The data run was plagued by difficulties in establishing new operating points for the machine,

Figure 10 Dependence of beam brightness on peak measured diode voltage. Voltage variation was obtained by two methods; varying the system charge voltage, and "dropping cores" (see text).

and as a result the data obtained is suspect. However, the fact that no variation in beam brightness with accelerating voltage was observed in this data suggests caution in drawing the conclusion that increasing the accelerating voltage is the key to obtaining much higher beam brightnesses.

The "standard" diode configuration was investigated in four sets of measurements using four different cathodes. Two cathodes were constructed using velvet supplied by MRC and two with velvet purchased in Livermore. The results of these experiments are shown in Figure 11. The scatter in the plotted data indicates the lack of reproducibility in the measurements, which has made it difficult to draw conclusions from the experiments. Changes in beam brightness due to intentional systematic changes in geometry were typically overwhelmed by the scatter in the data.

Figure 11 Dependence of beam brightness on peak measured diode voltage for four different cathodes made from velvet obtained from two sources. Standard diode geometry as in Figure 1.

SECTION 6

COLLIMATOR - BRIGHTNESS MEASUREMENTS

6.1 Characteristics

Beam brightness was inferred from the current transmitted through a small diameter pipe immersed in a strong, uniform magnetic field. The brightness calculation was based on a simple equilibrium³ analysis which neglects space charge and variations in the phase space density and in the magnetic field resulting in the expression $J = 6 I r^4 / \gamma^2 \beta^2 a^4$, where a is the radius of the collimator pipe and r is the Larmor radius ($r = \gamma mc / eB$). Thus, in this model, the only parameters needed to determine the beam brightness are the magnetic field strength, the collimator radius, and the transmitted current.

The collimator radius was 0.79 cm. The axial profile of the axial component of the applied magnet field is shown in Figure 12. The data points represent measurements⁴ made with a Hall effect Gaussmeter, and the curve is the result of a calculation of the field using measured coil currents and parameters. The collimator was installed prior to these experiments and was inadvertently connected with reversed currents in the coils. While this error does not invalidate the measurements, it does place increased emphasis on the need for realistic modeling of the collimator. The calculation of the beam brightness used an average value of 750 Gauss for the conditions indicated in Figure 12. The effects of a nonuniform magnet field have not been addressed. The magnetic field in the collimator is principally determined by the currents in three coils (F22, F23a, and F23b). When the field was varied, the ratios of the currents in these coils was kept constant. Unfortunately, this procedure also shifts the location of the magnetic cusp as the collimator field is varied.

Figure 12 Axial variation of collimator magnetic field. Location of collimator is indicated. Variations in collimator field were obtained by keeping the ratios of currents in the magnets F22, F23a, and F23b constant.

is varied. The current used in the brightness calculations was the peak current measured by BB2.

6.2 Tuning

Ideally, the beam optics upstream from the collimator should be set to produce a beam which propagates at a constant radius larger than the pipe radius in the applied field. Under these conditions, an equilibrium model should apply. No attempt was made to verify that the measurements were being made under these conditions. Instead, it was assumed that maximum current transmission would be achieved at equilibrium and, therefore, tuning the transport system to maximize the transmitted current was equivalent to obtaining the best approximation to equilibrium conditions. This tuning of the transport system was done manually by the machine operator, and involved setting the currents in the bucking coil, eight focussing-transport magnets, and one pair of steering coils. The tuning was not performed in accordance with a specific procedure, but rather represented the best effort of the operator at each time. Different operators obtained nearly the same transmitted currents with similar tunes, but the sensitivity of the results to operator dependent effects was not addressed.

6.3 Near Field

Numerical simulations of electron trajectories in the diode show that the phase space density of the beam is far from uniform at the entrance to the anode bore. Nonlinear effects in the beam transport system distort the phase space volume occupied by the beam and cause the phase space density to become homogeneous, at least on a macroscopic scale. This process requires the beam to be propagated over some distance. Measurements made closer to the beam source than this distance may not accurately reflect the characteristics of the beam at the exit of the accelerator. In the optics sense, the region of the transport between the source

and the point at which the mixing is complete is the "near field" of the source.

There are strong indications that the collimator was located in the near field of the beam during these experiments. Beam profiles as measured with the gated television system clearly showed that beams at that location just upstream of the entrance to the collimator retain the spatial characteristics of the cathode used to generate them. Specifically, beams generated with an annular flashboard cathode were still hollow at the viewing port.

In order to measure the beam brightness with the collimator, the acceptance of the collimator must be totally contained within the emittance of the beam, and preferably should be smaller than the characteristic length associated with gradients in the phase space density. While this condition may be satisfied for the angular dimensions in phase space, it is at best only marginally true for the spatial dimensions. Beam profile measurements under optimum tune conditions show a beam radius of 0.9 cm at the viewing port compared with the collimator radius of 0.79 cm. Variation of the focussing strength of the last transport magnet indicate that the beam waist at optimum tune is downstream from the viewing port, and thus the beam radius at the entrance of the collimator may be smaller than that measured at the viewing port. Whether it is smaller than the collimator could not be determined with the available diagnostics.

These concerns suggest that the brightness calculated from the transmitted current probably represents a lower bound on the actual beam brightness.

6.4 Magnetic Field Scans

Since the angular acceptance of the collimator is proportional to the square of the magnetic field strength, the varia-

tion of brightness with collimator field should give some information about the distribution of the phase space density. If the density is uniform within the phase space ellipsoid, the brightness should be independent of magnetic field. Figure 13 shows two cases where the collimator field was varied with the same 1 cm high convex cathode. The lower set of points was obtained by optimizing the transport tune with the collimator field at its maximum (750 Gauss at 126 Amps) and then reducing the collimator field without altering the tune. Under these circumstances, the brightness is relatively independent of magnetic field. The upper set of points was obtained by reoptimizing the transport tune for each value of collimator field. The resulting dramatic increase in inferred brightness at low magnetic field might indicate the presence of an extremely bright beam core (in phase space). However, the length of the collimator pipe is only about 0.8 times the cyclotron wavelength of the beam at this field, and the simple analysis used to infer brightness is not valid under these circumstances. Numerical simulations are needed to determine if this measurement is potentially interesting or merely an artifact of the violation of the assumptions used in the analysis of the data.

It is clear that a greater understanding of the operating characteristics of the collimator, and more information about the properties of the electron beam are necessary before the values of brightness inferred from the data can be accepted as representative of the performance of the beam.

1CM DOWED VELVET, EMITTANCE SCAN, TUNED

S20805.E FRAME: 11
15-OCT-84 FC/10/16/84

BRIGHTNS:

BEAM GAUSS = 5.7000E+00
BEAM BETA = 9.8449E-01
H COLLIMATOR (GAUSS) = 7.4970E+02
K CYCLOTRON (CM-1) = 7.8713E-02
L CYCLOTRON (CM) = 1.2786E+01
PIPE DIAM (IN) = 6.2500E-01
PIPE RAD (CM) = 7.8375E-01
F22SCALE (GAUSS/AMP) = 5.9500E+00
SCALE952 = 1.0000E+00

FILES:

S20804.E
S20805.E

Figure 13 Dependence of inferred brightness on collimator magnetic field strength. Lower points are for a fixed "accelerator tune" optimized at the highest field (750 Gauss at 126 Amps). Upper points obtained by retuning for each field. Highest inferred brightness displayed corresponds to a cyclotron wavelength 1.2 times the length of the collimator.

SECTION 7

BEAM EXPERIMENTS

7.1 Introduction

In order to address the goals of this effort, a series of experiments were conducted involving systematic variations in diode parameters. The parameter variations were selected to test various hypotheses concerning the mechanisms which determine the brightness in a particular diode configuration. The hypotheses focussed on two areas - cathode phenomena and electron optics in the diode. The brightness of the electron beam is influenced by uniformity, temperature, and motion of the plasma source. This in turn can be influenced by the cathode breakdown mechanism, cathode surface uniformity, uniformity of emission site density, plasma initiation time, electric field enhancement, and applied electric field strength. The electron optics are determined by the diode geometry (including the cathode shape), the distribution and strength of the applied magnetic field, the accelerating voltage, and the distribution of the beam's space charge.

7.2 Voltage Dependence

As stated above, the experiments performed included changes in the cathode material, emission site density, cathode shape, anode-cathode spacing, and accelerating voltage. The entire ensemble of the brightness data is shown in Figure 14 where no attempt has been made to differentiate between the various configurations used. It is clear that the beam brightness involves more than just the accelerating voltage. However, the separation of the data into classes, as discussed below, does show that the data below $6 \times 10^3 \text{ A}/(\text{cm}^2\text{-rad}^2)$ and above 2 MV generally corresponds to extremes in the configurations investigated. The remaining data falls roughly along a line proportional to $V^{3.5}$, as

Figure 14 Plot of all of the brightness data obtained by scanning the acceleration voltage with velvet cathodes except for those cathodes whose surface was intentionally degraded. Inclusion of data below 6×10^3 obscures the voltage dependence indicated in Figures 10 and 11.

does much of the data from individual configurations. The scatter in the data is sufficiently large to prevent a firm conclusion. Attempts to relate this restricted data set to other simple parameters were not successful, as described below.

7.3 Electric Field Dependence

A variety of hypotheses suggest that beam brightness may be dependent on the electric field strength at the cathode surface. High electric fields (at constant risetime) could be expected to produce a denser, more uniform plasma. A simple scaling argument⁵ suggests that brightness should be proportional to current density which is increased by higher applied fields. Figure 15 shows much of the data of Figure 14 replotted with the on axis vacuum electric field as the independent variable. The horizontal scatter in the data is substantially increased by this presentation. Of course, the on axis field is not representative of the average field for all geometries. Corrections involving the use of the average of a power of the electric field strength over the cathode surface do not improve the correlation of the brightness data to the electric field strength.

Early experiments showed a striking correlation between the beam emittance and the vacuum electric field for planar cathodes. The ratio of the beam brightness to the current incident on the collimator is proportional to the inverse square of the emittance. This data for the first two configurations tested is shown in Figure 16. The ratio of the electric field to the applied voltage differs by a factor of 1.3 for the two geometries, yet the data is remarkably consistent. The two experiments were performed with two different pieces of the same sample of velvet. Unfortunately subsequent experiments did not reproduce this behavior as shown in Figure 17.

Figure 15 Plot of data in Figure 14 as a function of the peak electric field strength on the cathode axis, neglecting space charge.

Figure 16 Early experiments with flat velvet cathodes indicated a consistent relationship between the beam emittance and the vacuum electric field. Note that the ratio of brightness to current incident on the collimator is proportional to the inverse square of the emittance.

Figure 17 Inclusion of all of the data of Figure 14 as treated in Figure 16.

7.4 Conducting Cathodes

Two experiments were performed with carbon fiber cathodes in order to determine if there is a fundamental difference between cathodes constructed from conducting and nonconducting fibers. The results of these experiments are shown in Figure 18 where the brightness obtained with flat carbon tufted cathodes as described above is compared with the performance of velvet cathodes in the same diode geometry. The difference between the velvet and sparse carbon fiber cathode is too large to be explained by scatter in the data. However, the comparison is somewhat suspect because the construction techniques were vastly different. The gross surface of both of the carbon fiber cathodes is far from planar which may account for some of the observed difference between them and the velvet cathodes. A more conclusive demonstration of the superior performance of nonconducting cathodes would be to construct one of a yarn woven and trimmed in the same manner as used to construct the carbon fiber cathodes. Surprisingly, the dense carbon fiber cathode produced a beam with substantially less brightness than the sparse cathode. The measured fiber density for the dense cathode implies an average fiber spacing of 30 microns compared with the 8 micron fiber diameter. This may reduce the field enhancement at the end of the fibers to the point where plasma formation is inhibited.

7.5 Other Velvet Cathodes

The other experiments performed in the standard geometry (flat cathodes with 12 cm anode-cathode spacing) are shown in Figure 19. In one experiment, a flat velvet cathode which had been used previously was "degraded" by removing the velvet fibers from several 1 cm² areas including one at the cathode center. Approximately 30% of the total area was affected. The reduction in brightness was significant. Measurements with a cathode constructed with "dense" velvet were disappointing. However, subsequent electron micrographs showed that the density of this material

Figure 18 Beam brightness produced with conducting fiber cathodes compared with velvet cathodes in standard diode geometry.

Figure 19 Beam brightness for different flat velvet cathodes.

was no higher than that of the other velvets used, in spite of its appearance. A substantial reduction in brightness was observed with a flat cathode with a one inch diameter hole in its center. Such a reduction was not observed in the ATA experiments.²

7.6 Diode Geometries

A large number of experiments were performed with velvet cathodes in different diode geometries. Although the principal intent of these experiments was to determine the effects of electron optics on beam brightness, each change in geometry also changed other parameters which might influence the brightness of the beam. The results of these experiments are shown in Figure 20.

The highest beam brightness was obtained with a convex (or dome) cathode and an anode-cathode spacing of 12 cm. However, the flat cathode, setback flat cathode, and convex cathode at a 14 cm spacing achieved nearly the same brightness in spite of the obvious differences in electron optics.

The concave (or dish) cathode produced a beam with a very low brightness even though the setback flat cathode and concave cathode both produced electric potential distributions whose contours are concave on the beam axis. However, the radial variation of electric field strength at the cathode surface is very different for these two cathodes. The peak electric field for the setback geometry occurs on the beam axis and diminishes as the radius is increased. The cathode edge is well shielded electrostatically by the cathode shroud. The concave cathode has a maximum electric field at the edge of the cathode. While the cathode current distribution was not measured, it is reasonable to assume that the setback cathode produces a current profile that is peaked on axis and disappears smoothly with increasing radius. The concave cathode would have a current profile peaked at the beam edge producing a somewhat hollow beam. It is possible

Figure 20 Beam brightness produced from different diode geometries with velvet cathodes.

that the brightest portion of the beam is produced near the beam axis and is selected in the measurement by the tuning of the accelerator to maximize the current transmitted through the collimator.

The geometries which employed anode-cathode spacings of 10 cm produced beams with lower brightness than their corresponding 12 cm spacing beams. For the flat cathode, the difference in measured brightness is within the typical scatter in the data. While it is possible that these beams are influenced by current emitted from the surrounding shroud at these high fields, the cathode shroud current monitor did not show an increase in the total current that was not consistent with the increased beam current. The more likely explanation is that the convex cathode crosses a threshold in the electron optics (perhaps virtual cathode formation) as the anode-cathode spacing is reduced from 12 to 10 cm.

The "Neumann" geometry, designed by Art Paul,⁵ was also tested with disappointing results. EBQ calculations predicted an optics limited brightness of $10^6 \text{ A/(cm}^2\text{-rad}^2\text{)}$, while the measured brightness was substantially less than for other geometries tested.

With the exception of the concave, "Neumann", and convex-10 cm geometries, there is little evidence that electron optics is strongly influencing the beam brightness.

SECTION 8

EBQ CALCULATIONS

8.1 Introduction

A series of numerical simulations of electron trajectories in the standard diode geometry were made with the EBQ computer code.⁶ This code is, in principle, capable of performing a fully self-consistent simulation in which the electron beam current is locally dependent on the electric field near the cathode surface which is, in turn, determined by the local space charge associated with the electron beam. For this type of calculation, EBQ assumes that the beam is divided into a specified number of rays starting on an equipotential surface near the cathode. The current for each ray is determined by applying a nonrelativistic, planar form of Child's law to the region between the starting surface and the cathode. Since the applied electric field is nearly cancelled by the beam's space charge electric field near the cathode, the potential of the starting surface is a sensitive function of the electron optics in the diode.

8.2 Method

One of the major difficulties in using the EBQ code is in selecting a set of starting conditions and a methodology which will converge to a calculationally stable solution. EBQ uses over-relaxation on the total beam current to achieve convergence. Unfortunately, the total beam current can and does converge to a stable value without achieving local convergence. Space charge averaging was used to supplement the total current relaxation. The space charge calculated from the ray tracing on each iteration was averaged with that stored from previous iterations at each grid point in the problem.

Further enhancement in the rate of convergence was achieved by artificially stopping the rays at an axial location inside but near the entrance of the anode as shown in Figure 21. This simulation was followed for twelve iterations until the solution neared convergence. The space charge array downstream from the trajectories was then loaded with a uniform space charge density consistent with the calculated beam current, and the calculation resumed.

The calculation did not converge to a solution, but rather achieved a stable oscillation whose extremes are shown in Figures 22 and 23. The oscillation amplitude remained constant to three significant figures over several cycles before the simulation was terminated. A total of fourteen iterations were calculated after the trajectories were allowed to propagate through the entire problem. Trajectory starting conditions were stored on two successive iterations representing the extremes of the oscillation. Each of these constant starting conditions was used in two separate calculations which converged in four iterations to a stable solution (Fig. 24). The resulting solutions do not achieve space charge limited flow since the starting conditions were not allowed to seek a self-consistent relation between trajectory currents and the electric fields. The resulting currents differ by only six percent, and of course result from the extremes of the "self-consistent" solution.

8.3 Brightness

The beam brightness, as calculated from the phase space output of the EBQ code, is shown in Figure 25 as a function of the axial distance from the cathode. Three curves are plotted; two of successive iterations from one starting condition, and one from the other starting condition. All three cases yield similar brightness over most of the axial distance. The three cases begin to diverge approximately one pipe diameter from the end of the calculation, which could be the result of the unphysical

CELL .2500 X .5000
 BMIN BMAX= -.031 535.478
 12.0

t= 0.

Figure 21 Start of EBQ calculation. Trajectories stopped at entrance to anode bore. Note that the horizontal scale has been compressed by a factor of three.

CELL .2500 X .5000
BMIN BMAX= -.031 535.478
12.0

I= 2384.1

Figure 22 Full EBQ calculation using self-consistent
(Child's law) trajectory starting conditions.

CELL .2500 X .5000
 BMIN BMAX - .031 535.478
 12.0

1= 3876.1

Figure 23 EBQ iteration following Figure 22. Solution is in a stable oscillation between the conditions of Figures 22 and 23.

.2500 X .5000
 BMAX= -.031 835.478
 12.0

I= 3078.9

Figure 24 EBQ calculation with fixed trajectory starting conditions as in Figure 22. Current converges to value shown.

Figure 25 Beam brightness calculated for the results of the EBQ diode simulations. Axial distance measured with respect to the cathode. Lower branch of each curve ($z > 36$ cm) includes all of the trajectories; upper branch excludes the outermost trajectory.

boundary condition imposed at $z = 64.5$ cm, or could be the result of the expansion of the pipe to a larger diameter in this region.

The drop in calculated brightness for $z > 40$ cm (heavy lines) results from the inclusion of the outermost trajectory in the simulation. Omission of the outer trajectory produces the lighter curves. The anomolous behavior of the outer trajectory as shown in Figure 24 could result from a simulation difficulty at the apparent intersection of the trajectory and the anode pipe.

The calculated brightness is at least an order of magnitude higher than the values inferred from the experimental data up to an axial location of $z = 40$ cm. The calculated brightness remains an order of magnitude higher if the outer trajectory is omitted. Unless the degradation of the beam near the axial extreme of the simulation is correct, gun optics is not the mechanism which is limiting the measured brightness. Further EBQ simulations are needed to resolve this issue.

SECTION 9

ETA - ATA COMPARISON

The results of experiments performed on ATA achieved higher values of brightness than did the experiments on ETA. The difference has not been resolved, however, there are differences between the experimental configurations, gun characteristics, and the collimators used to infer beam brightness. Figure 26 shows the brightness data from the standard configuration of ETA together with a data set from ATA. The ATA data is uniformly higher and its voltage dependence is weaker.

The diode geometries employed in the ATA and ETA experiments differ, but not significantly. Their similarity together with the wide range of diode geometries tested in ETA make it unlikely that geometry differences explain the brightness measurements. The applied electric field strengths were similar, the cathodes were made from the same piece of velvet, the beam areas differed only by a factor of 1.6, and the anode-cathode spacings were similar (12.9 vs. 10-16 cm).

The most striking differences between the experiments involved the temporal profiles of the voltage and current pulses. The ATA voltage pulse's risetime is a factor of two shorter than that of ETA, which could lead to the formation of a denser and more uniform plasma cathode. In addition, the waveforms generated by ATA are flatter than those of ETA. Figure 27 shows the current transmitted through the ATA collimator and should be contrasted with Figure 7 for ETA. The maximum measured brightness occurs before the peak of the measured voltage on ETA while it is virtually constant on ATA. While circuit simulations show that there is a time difference between the peak measured voltage from ETA and the peak accelerating voltage developed across the anode-cathode gap, the simulations indicate that there is little difference in the peak

Figure 26 Comparison of beam brightness results from ATA and ETA experiments. Collimators and diode geometries differ.

C26601.A FRAME: 15
3-OCT-84 FC/10/08/84
SCOPE NO: 1 SIGNAL NAME(1): BB12 FULL SCALE VOLTAGE = 9.3852E+00

Figure 27 Current waveforms for beams transmitted by the ATA collimator. Contrast with Figure 7 for ETA.

magnitude of the measured and accelerating voltages. Thus, voltage differences do not appear to account for the difference in inferred brightness.

The ATA collimator is larger in diameter and operates at a higher magnetic field than the ETA's. While this is not expected to affect the measurement, it cannot be completely ruled out as a possible explanation for the differences.

SECTION 10

CONCLUSIONS AND RECOMMENDATIONS

There is only one definite conclusion that can be reached as a result of the ETA experiments; that they achieved a measured brightness that is a factor of two higher than obtained previously. There is at least one exception to any trend in the data that would lead to a conclusion regarding the physical mechanism responsible for limiting the beam brightness. There is, however, a great deal of information to suggest directions for further work which could lead to improvements in brightness. These conclusions and recommendations fall into several general areas; the measurement technique, the characteristics of the ETA electron gun, electron optics, and cathodes.

10.1 Collimator

Numerical simulations are needed to determine if the behavior of the collimator can be adequately described by the simple equilibrium model used to infer brightness from the transmitted current. It is conceivable that the brightness measurement is limited by saturation of the collimator rather than by beam formation. The collimator field is far from uniform and extends well beyond the collimator entrance. Different field coil configurations should be considered to make the field geometry easier to interpret. The location of the collimator should be considered further (near field vs. far field) so that the measurements are meaningful for their intended use. A repeat of some of the experiments should be performed with the current in the collimator field coils reversed so that a cusp is not formed upstream from the collimator.

Little information concerning the characteristics of the beam incident on the collimator was obtained in the ETA experi-

ments. Tuning the accelerator for maximum transmitted current was substituted for detailed knowledge of the input conditions. This may be a reasonable approach if the emittance of the beam is much larger than the acceptance of the collimator, but this condition was not satisfied in the experiments. In order to determine the applicability of the equilibrium model (at least partially), the beam position, size, and profile should be measured at the collimator entrance. In addition, an attempt should be made to measure the beam envelope upstream of the collimator to assess its equilibrium.

An "emittance box" measurement would be a useful cross-check of the collimator measurements, if the ETA brightness fits within the measurement "bandwidth" of the device. These measurements would have to be time resolved and correlated with the transmitted current signals.

More "real time" diagnostic capabilities should be provided for experiments. Data as well as time was lost because of the forced delays involved in off-loading and transporting the data to remote locations for analysis. Some real time capabilities did exist but they should be expanded.

10.2 ETA Gun

The most striking feature of the brightness data is its strong dependence on the accelerating voltage. Of course, there are exceptions in the data, but nearly all of the cathodes and diode configurations exhibited this behavior. Since the voltage pulse shape in ETA is nearly independent of the operating voltage, the rate of rise of the electric field is proportional to the voltage and could lead to improved plasma cathode properties. However, the data from experiments in which the anode-cathode spacing was varied does not show a similar strong dependence on electric field, which is not consistent with this explanation of the voltage dependence. Dismissing this objection on the basis

of electron optics changes as the anode-cathode spacing is varied appears inconsistent with the rest of the geometry data and the EBQ calculations. However, the evidence supporting this statement is far from conclusive.

There are two mechanisms involving small-scale irregularities of the cathode surface which can produce an increase in brightness with increasing voltage. However, it is difficult to see how they can lead to a dependence which is as strong as that observed. A small-scale perturbation in the cathode surface produces a transverse component to the electric field which depends on the scale length and amplitude of the perturbation, and, in the absence of space charge, is proportional to the applied voltage. The transverse velocity acquired by an electron passing through the perturbation is proportional to the electric field strength and to the transit time of the electron through the perturbation. If the perturbation is sufficiently small, the electron energy will remain nonrelativistic as the electron passes through it, and the transit time will decrease as the square root of the voltage. Combining these effects with the voltage dependence for the space charge limited current density yields a brightness which increases roughly as the square root of the applied voltage; far weaker than observed.

The second mechanism related to a perturbation in the cathode surface involves a relativistic effect and is difficult to reduce to a functional form. The presence of space charge in a nonrelativistic diode leads to an electric field of the form $E = (4/3)(V/d)(x/d)^{1/3}$ where x is the axial distance from the cathode surface, V is the applied voltage, and d is the anode-cathode separation. In the ultra-relativistic limit, the electric field has the form $E = 2(V/d)(x/d)$. As a result, the electric field in the vicinity of the cathode ($x/d \ll 1$) which determines the strength of the transverse component of the electric field is larger for the nonrelativistic case. Thus, the transverse component of the electric field should change more slowly than

the applied voltage resulting in a stronger dependence of the brightness on voltage.

The exceptions in the data cast some uncertainty over the conclusion that beam brightness can be increased substantially by increasing the accelerating voltage applied to the anode-cathode gap and exploiting the strong voltage dependence observed in most of the data.

Improvements in the ETA system, which would provide shorter risetimes and flatter voltage pulses, should be encouraged. However, there is no evidence in the experimental data for ETA alone that such changes would lead to increased brightness. Such changes would increase the beam energy available at maximum brightness and would facilitate the interpretation of data.

Better accessibility to the diode region of ETA, particularly from the anode side, would permit a broader range of experiments and expanded diagnostic capabilities.

The diagnostics available in the ETA gun should be improved. There appears to be a great deal of uncertainty surrounding the accuracy and fidelity of the voltage monitoring system which should be corrected. A total cathode shroud current monitor should be developed. This may involve no more than repositioning the existing monitor. A monitor for measuring the current injected into the anode bore would be a useful addition to produce information on electron optics.

10.3 Electron Optics

There are a great many questions concerning electron optics that can be addressed with numerical simulations. The EBQ simulation described above has not been carried far enough to reach a conclusion. One important question is whether the brightness of the beam as calculated at 40 cm from the cathode is preserved as

the beam propagates? The decline in brightness at > 40 cm may be the result of the modeling rather than the physics. In addition, the beam should be followed further into the transport region. If the brightness is preserved, then it is being limited by cathode phenomena rather than by optics. If the brightness is not preserved, then attention can be directed towards its preservation in the transport region since the aberrations associated with the entrance of the beam into the anode bore are probably not responsible for the degradation beyond 40 cm. If the beam brightness is not being preserved during propagation, then the increase in anode pipe diameter should be considered as a possible cause of the degradation.

EBQ can be used to address the voltage scaling issue. It would be desirable to determine if electron optics in itself leads to a strong dependence of brightness on accelerating voltage. In addition, higher electron energies may make preservation of the beam brightness easier to accomplish in the transport system.

EBQ also could shed some light on the experiments involving changes in the diode geometry, particularly the poor performance of the beam produced with 10 cm anode-cathode spacings. Such calculations might have little meaning if electron optics is found not to be the brightness limiting mechanism.

Better diode designs may be possible, although it does not appear that the experiments have reached that limit. It may be possible to design an experiment to confirm the role of optics in determining the brightness. However, it is clear that such experiments should be designed with the aid of simulations rather than simply trying another geometry.

10.4 Cathodes

The continuation of the cathode development work described in this report should address at least three issues; (1) a compar-

ison between conducting and nonconducting fiber cathodes, (2) improvement in the reproducibility of the data, and (3) manufacture of smoother, more uniform surfaces. Surface flashover of an insulator may produce a denser, cooler plasma cathode than that obtained from conducting materials, but the cathodes tested were not sufficiently similar in their construction to justify such a conclusion. The cause of the scatter in the experimental data is not known, but the candidates are subtle changes in the pulses applied to form the beam, differences in the specific pieces of cathode material used, and environmental differences in ETA. Smoother, more uniform cathodes may lead to more reproducible behavior, may produce brighter beams, and will permit the study of small scale variations in the cathode structure.

Since carbon fiber velvet with the same physical characteristics as the velvet used in the experiments is probably not available, it would seem more reasonable to develop a manufacturing method which could be used with both conducting and nonconducting fibers. Conducting fibers could be either metal, semiconductors, or resistive materials such as carbon. Nonconducting fibers could be either plastic, glass, or perhaps a crystalline insulator. Fibers could be manufactured at a regular spacing by drawing an array of larger fibers to a locally smaller diameter. "Lost wax" methods could be used; that is, imbedding an array of fibers in a matrix of a dissimilar material which would permit machining the cathode surface, and then removing the matrix by thermal or chemical methods. Such techniques could address items (1) and (3) above, and possibly impact (2) as well.

Another fabrication technique suggested by John Weir⁷ is to photoetch an array of projections onto a substrate by processes familiar to the integrated circuit industry. There are two characteristics of the velvet cathodes that may be difficult to reproduce in this way. The aspect ratio (height to width) of the velvet fibers is about 300 to 1, and the edges of the fractured ends of the fibers have a radius of curvature of less than 0.1

micron. These features may not have to be reproduced. This fabrication technique certainly provides for detailed control of the cathode surface.

A candidate for a nonconducting cathode is a microchannel plate which does not have the secondary emission material coating. These materials are composed of an array of glass tubes typically with 12 micron bores arranged on 15 micron centers producing a site density of 5×10^5 per cm^2 and a total insulator surface area several times larger than that of the velvet materials. They can be ground to optical flatness. The major disadvantages are cost and a high effective dielectric constant (~ 2) which may make achieving flashover fields difficult.

The major approach to achieving better reproducibility would be through the fabrication of cathodes with more repeatable characteristics. More careful measurement of electrical parameters of ETA and controlled experiments with background pressure might shed some light on this problem.

Alternatives to the fiber cathodes and other "field emission" cathodes should be considered. The most obvious involve actively produced plasmas and smooth surface emitters. Improved flashboards, involving higher site densities, higher power drives, and better isolated arcs, would provide more uniform and denser plasmas but perhaps at higher temperatures as well. Streaming plasma guns and puffed gas discharges are also possible. Smooth emitters include thermionic and photoelectric cathodes. Thermionic cathodes employing controlled porosity or dispenser substrates may be able to survive the poor vacuum and contamination problems of the injectors. Photoelectric cathodes using hard ultraviolet sources, flash cleaning prior to each pulse, or perhaps CsI might also be able to survive in this environment.

"Off line" experiments are appropriate for alternative cathodes where the basic question is "will it work?". However,

meaningful brightness measurements can only be made at significant voltages and currents, and with lifetime an issue, this mandates the use of ETA or a similar facility. Off line experiments are also appropriate for basic physics experiments involving the nature and limitations of the emission mechanism.

SECTION 11

SUMMARY

The beam brightness experiments performed on ETA have produced an electron beam using a velvet cathode whose brightness is a factor of two higher than previously measured for beams generated from a flashboard cathode. The experiments also indicate that further analysis of the collimator used to measure beam brightness is warranted to assure the validity of the techniques used to infer brightness from the transmitted current. Additional EBQ calculations are needed to determine if electron optics is responsible for limiting the beam brightness. If electron optics is the limiting mechanism, then attention should be directed to preserving the brightness of the beam during transport. Experiments are needed to conclusively establish the superiority of nonconducting cathodes.

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APPENDIX A

Cathode Evaluation Summary

The following table lists the results of a series of experiments using flashboard cathodes which were performed on ETA before the experiments described in this report. The experiments performed between 8/3/84 and 8/8/84 used the same collimator as described above.

CATHODE EVALUATION SUMMARY

	DATE	CATHODE	BBI	B82	B82/ BBI	B.C.	F22	E*	Y [†]
↑	7/25	5" TRIPLE GAP	4.0	740	.185	5.5	90	.25	7740
	7/27	5" RADIAL	3.7	720	.194	5.5	90	.25	7530
1"									
IRE	7/27	5" RADIAL	3.83	904	.236	4.4	120	.214	9450
	7/27	5" DRWT	4.8	820	.170	?	90	.26	8570
	7/31	ORIGINAL	4.9	800	.164	4.6	120	.26	8370
↓	8/1	10" DRWT	5.9	800	.134	3.5	120	.29	8170
↑	8/3	5" TRIPLE GAP	4.6	156	.034	4.0	120	.24	11040
	8/6	5" DRWT	5.41	94.8	.0175	4.0	120	.349	6710
62"									
IRE	8/7	5" DRWT + AQUADAG	4.28	146	.034	4.0	120	.244	10370
	8/8	5" RADIAL + AQUADAG	4.14	187	.045	4.7	120	.267	13230
↓	8/8	5" TRIPLE GAP + AQU.	4.45	141	.032	4.5	120	.254	9980

* NORMALIZED RMS EMITTANCE, INCLUDES SPACE CHARGE

† BRIGHTNESS, NO SPACE CHARGE - NOT CALC.
FROM EMITTANCES