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AN INFORMAL REPORT

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Beam Measurements on the High-Intensity Proton Injector of LAMPF

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scientific laboratory
of the University of California
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BEAM MEASUREMENTS ON THE HIGH-INTENSITY
PROTON INJECTOR OF LAMPF

by

R. R. Stevens, Jr., S. D. Palermo, M. A. Paciotti, D. W. Mueller,
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ABSTRACT

Pepper pot and quartz plate measurements were made near the exit of the accelerating column over a wide range of operating parameters. Phase space envelopes were accurately determined; however, density distributions are still in doubt.

I. SUMMARY

One of the basic problems encountered in doing transport calculations for the proton beam in the injector area of LAMPF has been that of determining the properties of the beam going into the transport line. Initial design calculations for the transport system assumed a beam envelope of ± 0.7 cm size and ± 7 mrad divergence. Subsequent studies¹ of the beam transport system indicated that the size and divergence of the beam entering the transport system were larger than originally considered, and that this larger input beam required a change in the focusing strength of the lenses in the transport system to prevent beam loss at the prebuncher. To do more realistic calculations for this beam transport system, the size, divergence, emittance, and effective current of the input beam to this system must be known. Therefore, extensive measurements were undertaken at the exit of the accelerating column to determine these parameters for a variety of operating conditions. This report discusses the measurements performed and the results obtained.

The program began and ended with a standard set of experiments involving x-ray radiation, proton ratio, and the transverse phase space at EM1, EM2 and EM3.¹ The main purpose of these before-and-after tests was to establish the validity of the more basic measurements. The first such measurement in-

involved a quartz plate positioned 16 in. from the exit of the column. Photographs of the beam impinging upon the plate were taken over a range of operating conditions. These gave corroborating evidence for the pepper-pot analysis and some intensity information.

The second set of measurements was made with a pepper pot located 5 in. from the exit of the column. A total of 104 photographs was taken over a wide range of operating conditions. All results obtained in these parametric studies are given in this report. Beam intensity information was obtained through a microdensitometer reduction of the pepper-pot dots.

Finally, a new single row pepper pot was installed, and intensity scans were performed using a TV vidicon device. This completed the present series of tests.

The measurements confirmed that the beam at the exit of the column is cylindrically symmetric. The three ion species occupy the same phase space. The beam is centered in the accelerating column; there is no measurable steering effect due to any of the operating parameters. Further, it is possible to explain the variation of x-ray radiation with beam current. It is apparent that the upper end of the curve is caused by the main body of the beam striking electrodes in the column, while the radia-

tion peak at the lower end is due solely to the halo, or tails, which constitute a much different phase space from that of the main body. The lower peak can be essentially eliminated by setting extractor voltage parametrically as a function of extracted ion current.

We define the beam envelope to contain the outermost visible portion of the main body of the beam as distinct from the tails. This identification is possible since the phase space of the main body of the beam in either plane is the area associated with a straight line passing through the origin. It is emphasized that the envelope, as such, gives no information concerning the intensity distribution of the beam within, save to confirm the uniqueness of that body of phase space.

It was found that the phase space envelopes are basically unaffected by any of the operating parameters, with the exception of extracted ion current. This variable produces a dramatic effect on all aspects of the beam. The main interest lies in the beam parameters near the operating current. At the center line of the tenth electrode, the beam phase space envelope has a size of ± 1.03 cm and a divergence of ± 14.6 mrad. The emittance is 1.25π cm mrad and the proton fraction is about 70%. Both the microdensitometer and the vidicon data indicate a very sharp drop-off of intensity for the main body of the beam. Both sets of data show that the radial position of this drop-off can be substantially reduced by changing arc magnet current. However, the two techniques used to measure intensity give results which differ by almost a factor of two in rms radius. This question has not yet been resolved. Thus, although we can define the phase space occupied by the beam, the precise population of that space is still uncertain.

II. THE ION SOURCE

The source for the high intensity proton beam is a duoplasmatron hot-cathode hydrogen arc discharge source. Figure 1 is a cross-section drawing of this source. The special feature of the duoplasmatron source is the axial magnetic field between the nose of the iron intermediate electrode (the cathode is inside) and the iron plasma-aperture fixture. There is some evidence that the axial field constricts the arc so that it passes through

Fig. 1. The duoplasmatron ion source.

the plasma-aperture and terminates on the far side of the hole (inside the cup). Thus, a hydrogen plasma is produced in the cup with a relatively small hydrogen gas flow. Hydrogen ions are extracted from the plasma by a strong electric field between the source and the extractor, about 25 kV across 1 in.

The designation for the particular source used in these studies is III a/11CT-2, which stands for source body III a, plasma aperture #11, and center-top cathode #2. Figure 2 is an enlargement showing more detail of the cup region. The Pierce anode hole diameter is 1.4 cm and the inner cup diameter is 1.6 cm. The original diameter of the plasma ap-

Fig. 2. Plasma aperture region of the source.

erture was 0.025 in. On December 17, 1971, this diameter was measured to be 0.031 in. The original depth was 0.010 in. and the iron rim radial thickness was 0.040 in.

This assembly had been in use in the 750 kV injector since July 22, 1971, and was still in use on January 28, 1972. Thus, it was well stabilized before the present measurements were made. On those occasions when the source was removed from the column, the cathode, intermediate electrode assembly, plasma aperture, and the Pierce anode were not disturbed relative to each other and to the main body of the source.

The proton fraction was measured as a function of extracted ion current both before and after the pepper-pot tests. These results are presented in Fig. 3. The cause of the slight drop in proton fraction after the tests is not known, but may simply be the result of improper tuning of the beam line. Other proton fraction determinations have subsequently been made which are closer to the original curve.

The source produces the emittance area of the beam. Previous measurements with emittance gear at the EMI station have indicated an emittance of 1.25 π cm mrad at the design operating condition. This figure is probably the same for all three species.

Fig. 3. Proton fraction measured as a function of total extracted current before and after pepper-pot tests.

Provision has been made in the design and construction of the source to allow for an increase in the cup depth. Spacers and spacer rings are provided for this purpose. These allow moving the body of the source back while the Pierce anode is kept in the same position relative to the extraction electrode of the column. This parameter was not explored in these experiments however, and thus its effect upon beam size and divergence is unknown.

III. THE ACCELERATING COLUMN

The 750-kV accelerating column and associated vacuum system are shown in Fig. 4. The position of the ion source is also indicated.

The electrode configuration in the accelerating tube is shown more clearly in Fig. 5. All electrodes and other metal parts of the accelerating tube are of highly polished 6Al-4V titanium alloy. Pump-out holes are provided in the electrodes to keep the pressure low, and they are staggered to reduce inline electron backstreaming. The electrode shapes are of Pierce geometry and were determined from a solution of Laplaces equation² to give zero radial acceleration to a uniform density, 50-mA pure proton beam of 6.9-mm radius. Contours for fabricating the electrodes are given in Table I. The last four electrodes are close approximations to the Pierce geometry, being straight for ease of fabrication, rather than slightly curved. The last two electrodes have larger apertures because of the exit aperture lens affect which, in theory, contributes a divergence of 1.09 mrad/mm of beam radius. Table II lists the axial position, diameter, and voltage for all electrodes.

The ninth electrode serves as an electron trap. It is biased at -10 kV to prevent electrons from entering the exit end and backstreaming up the accelerating tube. The electrode is thick to allow a large radius of curvature at the aperture to reduce the gradients where the equipotential lines curve around the electrode. With the trap biased at -10 kV, the calculated axial potential barrier is 2.4 kV for the simplified conditions assumed. The potential as a function of axial position is shown in Fig. 6 with the minimum occuring at the ninth electrode. Off axis, the potential barrier is larger, so that electrons must have an energy of at least 2.4 keV to overcome the barrier.

The effectiveness of the barrier is shown by the low x-ray radiation in Fig. 7. The component of

Fig. 4. The 750-kV accelerating column, ion source and vacuum system.

Fig. 5. Electrode configuration for the 750-kV accelerating tube. Energy level is indicated by the number on the electrodes and applied voltages are indicated on the titanium washers. The thick electrode at -10 kV is an electron trap which stops electrons from entering and backstreaming up the accelerating tube.

TABLE I
CONTOUR OF PIERCE ELECTRODES

Anode		#1 (extractor)		#2		#3		#4		#5		#6	
r (mm)	z (mm)	r (mm)	z (mm)	r (mm)	z (mm)	r (mm)	z (mm)	r (mm)	z (mm)	r (mm)	z (mm)	r (mm)	z (mm)
6.9	0	6.9	0	6.9	0	6.9	0	6.9	0	6.9	0	6.9	0
15.0	2.9	15.0	0.4	15.0	0.1	15.0	0.1	15.0	0.1	15.0	0	15.0	0
25.0	6.1	25.0	1.4	25.0	0.8	25.0	0.5	25.0	0.4	25.0	0.2	25.0	0.2
35.0	9.1	35.0	2.9	35.0	1.8	35.0	1.1	35.0	0.7	35.0	0.5	35.0	1.4
45.0	12.0	45.0	4.6	45.0	3.1	45.0	2.0	45.0	1.3	45.0	0.9	45.0	0.7
55.0	15.0	55.0	6.6	55.0	4.6	55.0	3.0	55.0	1.9	55.0	1.4	55.0	1.1
65.0	17.9	65.0	8.7	65.0	6.3	65.0	4.2	65.0	2.7	65.0	2.0	65.0	1.6
75.0	20.8	75.0	11.0	75.0	8.1	75.0	5.5	75.0	3.5	75.0	2.7	75.0	2.1
		85.0	13.3	85.0	10.0	85.0	7.0	85.0	4.5	85.0	3.4	85.0	2.7
		95.0	15.7	95.0	12.0	95.0	8.6	95.0	5.6	95.0	4.3	95.0	3.4
				105.0	14.1	105.0	10.2	105.0	6.8	105.0	5.2	105.0	4.3
						115.0	12.0	115.0	8.1	115.0	6.2		
								125.0	9.4	125.0	7.3		
										135.0	8.4		

#7	#8	Electron #9 Trap	Exit #10 Electrode
Taper	Taper	Taper	Taper
1° 58'	1° 25'	flat	flat

Note: Surface contour given for anode. Contour of electrode #1 is center line value and electrode starts at $r = 8.0$ mm. Contours of electrodes #2 thru #8 are centerline values and electrodes start at $r = 10.0$ mm.

TABLE II
PIERCE ELECTRODE GEOMETRY AND POTENTIALS

Electrode	Axial Position (cm)	Aperture Diam (cm)	Potential (kV)
Anode	0	1.38	750
#1	2.54	1.60	724
#2	4.28	2.00	696
#3	7.19	2.00	641
#4	12.09	2.00	533
#5	16.39	2.00	424
#6	20.34	2.00	316
#7	24.05	2.00	207
#8	27.57	2.00	99
#9	30.95	2.50	-10
#10	32.59	2.70	0

Fig. 6. Axial potential in the region of the electron trap. With -10 kV applied to the trap, the axial potential barrier is 2.4 kV.

Fig. 7. X-ray radiation as a function of electron trap voltage. Electrons can overcome the potential barrier if the trap voltage is reduced below -5 kV.

x-ray radiation produced by backstreaming electrons entering the tube and impacting the electrodes is negligible for trap voltages between -10 kV and -5 kV. Above -5 kV, the potential barrier is insufficient to stop the electrons, and the radiation rises sharply.

The extractor electrode, next to the Pierce anode, is connected to a separate power supply in the dome so extractor voltage can be set independently of column high voltage. This electrode is fitted with a replaceable insert which reduces the aperture from 2.0-to 1.6-cm diam. The purpose of this insert is to intercept divergent ions at the extractor instead of letting them strike subsequent electrodes at much higher energy. When the beam strikes the titanium electrodes upstream from the electron trap, the secondary electrons produced are free to backstream up the tube, producing x rays on impact. This x-ray radiation is shown as a function of total beam current in Fig. 8 for measurements made both before and after the pepper-pot tests. Radiation is low at the Pierce design current region (45 mA for a 70% proton fraction) because the beam space charge here is compensated by the Pierce geometry, so that the beam does not strike the electrodes. Radiation increases above the design current because the space charge becomes larger causing the core of the beam to diverge and strike the electrodes. Below the design current, measurements indicate that the radiation is caused by greatly expanded tails. Recent experiments based on theoretical analysis³ have shown that this radiation peak

Fig. 8. X-ray radiation measured as a function of total extracted current before and after pepper-pot tests.

can be eliminated by varying the extractor voltage parametrically with beam current. No change in extractor voltage is required near the Pierce design current.

In a measurement made after the pepper-pot tests, a substantial shift in the position of the lower end of the curve was noted. This shift can be seen in Fig. 8. It indicates that somehow the tails were larger in size and were thus scraping the electrodes. Similar shifts have been seen before and are believed due to small variations in ion source parameters.

IV. PEPPER-POT APPARATUS

A photograph of the assembled pepper-pot apparatus is shown in Fig. 9. The basic features are a titanium plate with an array of drilled holes, a quartz plate with ruled grid lines to match this array, and an observation window through which photographs are taken. The pepper pot was made of titanium to avoid the possibility of sputtering or evaporating a different material on the titanium electrodes in the column.

Fig. 9. The pepper-pot apparatus.

Fig. 10 is a photograph of the titanium pepper-pot plate taken from the beam side. The defining apertures, which are 0.005 cm in diameter, lie within the larger holes shown in this photograph. Information concerning the spacing of the equilateral triangular array is given in Table III. By the time this photograph was taken, the central and immediately surrounding holes had been melted shut. This melting also closed a 0.005 in. diam marking hole lying 0.020 in. to the left of the center hole of the array. There is evidence that the melting was

TABLE III
PEPPER POT
Equilateral Triangular Array

Horizontal spacing of the pepper-pot array and quartz plate grid	0.0938 in.
Vertical spacing of the pepper-pot array and quartz plate grid	0.0812 in.
Number of horizontal rows	15
Number of vertical columns	12 and 13
Diameter of defining apertures	0.005 cm

caused by failure of the modulator to turn off the beam at the end of the pulse, thereby greatly overheating the pepper pot.

As stated previously, the quartz plate had grid lines ruled on it on the side on which the beam strikes. The spacings of these ruled lines correspond to the base and altitude of the equilateral triangles of the pepper-pot pattern. A set of diag-

Fig. 10. The titanium pepper-pot plate.

onal dotted lines was used to mark the center of the grid. The lines were illuminated by a lamp inserted in a hole drilled in one corner of the plate.

For these experiments, the apparatus was installed on the accelerating column compression bellows flange as shown in Fig. 11. The axial positions of the pepper-pot elements with respect to the source and column are given in Table IV. An alignment measurement of the pepper pot with respect to the center line of the column was also made. A jig transit was aligned on the anode aperture and a lucite

TABLE IV
AXIAL POSITION OF PEPPER-POT ELEMENTS

Item	Axial Position (cm)
Pierce anode	-32.59
Extractor	-30.05
Center plane of #1 electrode	- 5.02
Center plane of trap electrode	- 1.64
Exit side of last electrode	0.00
Defining plane of pepper-pot holes	+12.80
Beam side of quartz plate	+25.13
Outside surface of viewing window	+35.6

target installed in the aperture of the tenth electrode. The pepper pot was found to be aligned vertically, but to lie 0.051 in. to the right, looking downstream, of the column axis.

To enable an accurate measurement of beam current striking the pepper pot and to determine the neutralization effect, it was necessary to bias the pepper-pot plate. For these tests, the plate was connected through a 150-V battery and a 100- Ω resistor to ground so as to bias it at +150 V with respect to the surrounding metal parts. The beam current produced a voltage signal across the 100- Ω resistor which was observed on an oscilloscope. The wire from the pepper pot to the biasing battery passed through a current transformer which also produced a voltage signal proportional to beam current. These two beam current measurements were observed to agree to within 5% throughout the pepper-pot measurements.

Current measured as a function of pepper-pot bias voltage is shown in Fig. 12. The curves become very flat above 120 V, indicating that almost all of the electrons produced at the plate were captured by the plate. Further evidence of this was provided

Fig. 11. The ion source, accelerating column, and pepper-pot apparatus.

Fig. 12. Current measured versus pepper-pot bias.

Fig. 13. Radiation as a function of electron trap voltage.

later in the experiments when the electron trap voltage was reduced from -10 kV to zero potential. The effect upon radiation produced is shown in Fig. 13. This result can be compared with that shown in Fig. 7, for which no biasing to remove electrons from the beam was done. Although different duty factors were involved, this comparison provides striking evidence of a high electron capture efficiency. The pepper-pot plate bias used in the tests and to produce Fig. 13 was 150 V. The 2 mA difference between the two determinations of the same current shown in Fig. 12 is probably due to improper gain of the current monitor amplifier. This discrepancy was removed just after the "A" series of pepper-pot photographs were taken. The current monitor and the 100- Ω resistor read identically for the remainder of the pepper-pot pictures.

The reentrant can of the column proved to be a difficult place to take photographs. An elaborate mechanical sliding track and locating pin arrangement was made so that the camera could slide out three or four feet for loading and then be repositioned to within a few mils. The 4x5 camera was critically focused with polaroid film and a micrometer lead screw.

V. QUARTZ VIEWING SCREEN MEASUREMENTS

A measurement of beam size near the exit of the column was made using a quartz plate viewing screen assembly installed onto the reentrant can at the exit of the accelerating tube as shown in Fig. 14. The quartz plate was viewed with a closed TV system, and photographs were taken of beam cross sections directly from the TV screen. The quartz screen was located 16 in. from the last electrode of the accelerating tube. A graticule was scribed on the quartz plate with 1-cm spacing.

The quartz plate was aluminized in order to drain charge from the viewing screen. This coating, however, was quickly sputtered away in the central region of the screen; some sparking was then observed on the quartz, but observations of the beam could still be made. Provision was made to bias the housing and quartz screen, but no difference in beam cross sections was observed when bias voltage was applied. The quartz plate may have been self-biasing after the aluminum coating was removed. In any event, the secondary electrons emitted by the quartz screen did not affect the beam measurements. The ion current to the quartz plate assembly was measured by passing the grounding wire from this

Fig. 14. The ion source, accelerating column, and quartz plate assembly.

assembly through a beam current monitor and observing the current pulse from this transformer.

Photographs were taken of beam sections for three arc magnet currents over a range of extracted ion currents from 10-46 mA. Figures 15-17 show the results for a 20 μ sec pulse width. Data on the beam size were obtained by visual interpretation of these pictures; results are plotted in Fig. 18.

In general, the beam size grows with increasing current extracted from the ion source. At 40 mA, the beam size appears to approach some limit, and thereafter increases only slightly. At lower beam currents, the beam size becomes smaller as the arc magnet current is increased. However, near the standard operating current, there is little apparent variation in beam size with arc magnet current. At an operating current of 46 mA, a beam size of 3.50 cm was measured on the quartz screen.

Photographs were also taken of beams with longer pulse lengths. The pictures shown in Figs. 19-21 were taken of a 100- μ sec pulse length beam using the three previously given arc magnet current settings. The beam sizes are essentially the same

as those obtained at 20 μ sec. The hollow structures and rings seen at lower currents are believed in large part due to beam heating effects in the quartz plate. These heating effects result in a decreased light output. Other measurements at the column and along the beam line have shown some evidence for hollow beam structures, but not to the extent suggested by these photographs. The microdensitometer and vidicon data presented later in this report are in substantial disagreement on this question. The beam heating effect is discussed quantitatively in the Appendix.

Another series of pictures, shown in Figs. 22 and 23, was taken at still a longer pulse length (180 μ sec) to study growth of the halo, or tails, as a function of extracted current. At low currents, a smaller central beam spot with a large halo is observed. At 10 mA, the beam core is 0.28 cm in diameter, and it is surrounded by a halo 2.7 cm in diameter. As the beam current is increased the beam spot and halo grow. At approximately 20 mA, the halo reaches a maximum size of 4.5-cm-diam and from that point on decreases in size with increasing current.

Fig. 15. Beam cross section with arc magnet current 1.50 A and pulse length 20 μ sec.

10 mA

20 mA

30 mA

40 mA

44 mA

46 mA

Fig. 16. Beam cross section with arc magnet current 1.75 A and pulse length 20 μ sec.

10 mA

20 mA

30 mA

40 mA

44 mA

46 mA

Fig. 17. Beam cross section with arc magnet current 2.60 A and pulse length 20 μ sec.

Fig. 18. Beam size versus extracted ion current.

At 40 mA, the halo disappears into the central beam spot. The peak near 20 mA agrees with the maximum observed in the x-ray background from the column at this current and with observations of the current picked up on the column electrodes.

The halo is also observed in beam cross sections at three viewing screens on the beam transport line. Figure 24 shows beam cross sections for Beam 6. We note that the amount of halo decreases with increasing current but is still present in the beam even at higher currents. Although the tails merge in coordinate space with the main body of the beam at the quartz plate, they represent a much different phase-space, and thus will reappear distinctly as halo at other points in the beam transport line.

VI. INTENSITY PROFILE MEASUREMENTS

Two different approaches were used to measure the variation in intensity across the beam. Both relied on interpretation of the light produced by beam striking the quartz plate of a pepper-pot apparatus.

Fig. 19. Beam cross section with arc magnet current 1.50 A and pulse length 100 μ sec.

10 mA

20 mA

30 mA

40 mA

44 mA

46 mA

Fig. 20. Beam cross section with arc magnet current 1.75 A and pulse length 100 usec.

10 mA

20 mA

30 mA

40 mA

44 mA

46 mA

Fig. 21. Beam cross section with arc magnet current 2.60 A and pulse length 100 usec.

2 mA

5 mA

8 mA

10 mA

20 mA

29 mA

Fig. 22. Beam cross section with arc magnet current 1.50 A and pulse length 180 μ sec.

34 mA

38 mA

40 mA

42 mA

43 mA

44 mA

Fig. 23. Beam cross section with arc magnet current 1.50 A and pulse length 180 μ sec.

Fig. 24. Beam cross sections for beam 6.

The first approach involved use of a TV vidicon device.⁴ For these measurements a single-row pepper pot was installed which had a hole separation of 0.234 cm and hole size of 0.005 in. The output from a single scan line from the pepper-pot image on a TV vidicon was obtained by using a delayed CRO (cathode ray oscilloscope) sweep of the proper length. The delay time, relative to the frame reference pulse, was adjusted to select the scan line running through a diametral horizontal row of pepper-

pot dots. The position of the vidicon was adjusted vertically with a micrometer screw so that the selected scan line ran through the centers of all the dots.

A neutral step wedge was used with a proper light source to relate the CRO amplitudes to relative light intensity. The relationship is shown in Fig. 25, and appears roughly linear. However, there is as yet no clear way to relate beam intensity to light intensity on the quartz screen. Therefore, work will continue on the analysis of these data.

Six of the intensity profiles are shown in Fig. 26. These were taken near the operating point for several different arc magnet currents. As is apparent from these photographs, the center-most hole had melted shut. However, the adjacent holes were not affected.

As can be seen by a comparison of the three photographs taken at 40 mA, arc magnet current appears to have a strong effect on the radial intensity of the beam. (It will be shown later that the phase space envelopes are basically unaffected by this parameter.) As the two photographs taken at 44 mA indicate, increasing the extracted ion current appears to have the effect of spreading the beam. The last photograph in Fig. 26 was taken at 48 mA, and at a different scale than the other 5 photographs.

The second approach to this problem involved reduction of the photographs taken for the phase space analysis. Intensity information on these

Fig. 25. Vidicon normalization curve.

40 mA
1.2 AMPS

48 mA
2.55 AMPS

40 mA
1.75 AMPS

44 mA
1.75 AMPS

40 mA
2.7 AMPS

44 mA
2.6 AMPS

Fig. 26. Vidicon scans.

photographs was retained by calibrating the response of the film. TRI-X Pan of ASA 320 has the minimum film speed for convenient exposures, and its use with D-76 and normal development of 9 min at 68°F gives an extended response curve. Figure 27 shows this characteristic curve. The film exposure was made through a calibrated step wedge. A 47B blue filter was inserted in a tungsten light source as a first approximation to the bluish appearance of the fluorescence from the quartz plate. Aside from reciprocity failure or differences between the fluorescence and tungsten light, the characteristic curve shows how to convert densities obtained by a microdensitometer into relative light intensities over the surface of the pepper pot. The wedges were exposed continuously for 60 sec; whereas the beam exposures resulted from pulsed light of 100 μ sec bursts at a rate of 15/sec for 60 sec.

A typical set of microdensitometer traces is shown in Fig. 28. These traces were taken of picture No. 7A through the centermost horizontal row. 7A was obtained with a column current of 44 mA and an arc magnet current of 1.75 A. Six scans were made through this horizontal row. The vertical spacing of these scans is shown in Table V. The fourth scan passed roughly through the spot center. The third trace passed along an illuminated grid line which shows up as a large background in comparison with the background in the other traces of the set. The largest peak is from the 0.005-in.

Fig. 27. Micro densitometer normalization curve.

Fig. 28. Photo densitometer scans.

diam locator hole, which lies 0.020 in. to the left of the center of the array. The column axis is 0.051 in. to the right of the indicated center hole, i.e., about half way between the center hole and the next hole to the right.

The grid lines show up as the very regular set of peaks especially noticeable in the top and bottom traces of the set. The array of pepper-pot spots representing beam core can be identified in the fourth trace by the seven central peaks, which are very uniform in height. The peak from the locator hole is roughly 20% higher, and the grid line peaks are about 60% lower.

For the intensity analysis, maximum photographic densities for individual dots were obtained by a horizontal and vertical search over each dot.

TABLE V
Vertical Spacing of Microdensitometer Traces

1	2.975 mm
2	2.475 mm
3	1.894 mm
4	1.700 mm
5	1.200 mm
6	0.700 mm

The area on the transparency for which an average density reading is obtained is 0.1 mm by 0.015 mm. A typical dot diameter, full width at half height on the density curve, is 0.5 mm. Thus, the density is averaged for a rectangle about 1/5 or less of the dot diameter in one direction and 1/30 of the dot diameter in the other.

Averages of the densities were then calculated for each of eleven circular increments centered on the column axis. The average film densities as a function of radius are plotted for four pepper-pot pictures in Fig. 29. A scale for corresponding light intensities taken from Fig. 27 is shown on the right-hand side.

The vidicon data (Fig. 26) and the microdensitometer data (Fig. 29) show qualitative agreement with respect to the effect of extracted ion current and arc magnet current. However, the two measurements are in marked disagreement regarding the actual intensity distributions. The rms radii from the vidicon data are roughly a factor of two greater than those obtained from the microdensitometer. Further, the microdensitometer data indicates a hollow beam, while the other does not. We are as yet unable to resolve these differences.

A beam intensity analysis is hampered by several factors. Only 6 pictures were taken before the pepper-pot holes in the central region were closed by heating, making intensity recovery impossible. Second, only one exposure of 60 sec was made for each parametric setting; this long expo-

sure was required to sufficiently expose the faint beam spots at the periphery of the pepper pot. The central region spot densities then were in excess of 2.6 where the film begins to saturate. The use of the calibration curve shown in Fig. 27 becomes much less accurate at the high end. Future experiments will require a range of exposures for each parametric setting.

Another factor in the conversion of spot density to light intensity that introduces error is the reciprocity failure of the film. Ten second exposures through the calibrated wedge were made and developed concurrently with each batch of film processing. In the actual data films, the 60-sec time rather than the 100- μ sec pulse time probably dominates the reciprocity failure of the film. Therefore, the 60-sec calibration curve (Fig. 27) is used rather than the 10-sec curves. The 10-sec curves serve as a measure of development reproducibility. The "GAMMA" or slope of the straight line portion for each of the 14 wedges developed did not vary by more than 10% from the average. However, a 10% error in the slope of Fig. 27 could introduce as much as a factor of two in the ratio of light intensity at the center of the beam to the intensity at the edge of the beam. As no wedge curve is available for the first 6 pictures in the experiment (the holes closed after the very first series) the above 100% uncertainty is believed to be the primary error in the conversion to light intensity. It will be possible in future experiments to generate the calibration curve with the beam itself when the first 60 μ sec of time varying beam phase space can be chopped away.

The conversion of beam intensity to light intensity on quartz must be known for all of the experiments in this paper. The Appendix indicates a maximum instantaneous temperature rise of only 10°C for the beam spot images on the quartz plate. This rise is well below the region where the quartz is known to give nonlinear and inverted response. Above a given temperature the light output falls with additional heating until thermal glowing brings the light up again. We will assume for the present that beam intensity and fluorescent light output are proportional for the pepper-pot data. The microdensitometer values were average densities over a 10- μ spot at the peak density of each dot. Figure 28

Fig. 29. Film density versus beam radius.

indicates that the density profile of a single spot on the film does not change significantly with the total beam current through the hole. That is, the profile scales with overall beam current, and the peak density is a good representation of the beam current through the pepper-pot hole. These questions can be answered with the same beam calibration experiment described previously.

In conclusion, intensity data are presented in this paper with a factor of two uncertainty in relative intensity of the center areas of the beam to the tail areas. The data can be further refined when a suitable on-line calibration experiment is performed. No errors have been assigned to the vidicon data. There exists the previously noted large systematic difference between the two intensity profile determinations. This difference represents our error in these measurements; work will continue towards resolution of this problem.

VIII. ANALYSIS OF PEPPER-POT DATA

To explore systematically the beam phase space at the exit of the column, a set of 104 pepper-pot photographs was taken over a wide range of operating conditions. A list of these photographs giving beam parameters and pertinent comments is presented in Table VI. The A and B series served as preliminary studies to the main parametric series, which is numbered 1-88. This latter series included as

Fig. 30. Pepper-pot picture No. 26.

parametric variables the extracted ion current, arc magnet current, extractor voltage, electron trap voltage, chamber pressure, and pulse width.

Shown in Fig. 30 is pepper-pot picture No. 26, which, according to Table VI, most nearly approximates the injector operating condition. By the time the main parametric series was started, the center-most hole and the locator hole had melted completely shut. The six adjacent holes had partially closed. This effect is evident in Fig. 30. It is also possible to distinguish between the regular array of spots representing the main body of the beam and the circularly shaped halo images adjacent to them. At the outer edge of the main body, the halo merges with it to create a tear drop shaped pattern.

The photographs were analyzed with the digitizing equipment from the Sherwood Project. Individual points were delineated by cross hairs, and x and y values recorded on punched cards. A computer program⁵ was used to interpolate the data and correct for nonlinearity in background grid resulting from photographic or projection distortions. For these calculations, only the core of the beam was digitized. Because of the large size and symmetrical shape of the data points, a determination of the exact center of each dot involved considerable subjective judgment. The positions of dots near the center of the pictures were probably more accurately determined than those near the outer edges, since the former were fairly circular and halos were discretely separated from the central spots. Toward the edges, the data points assumed a teardrop shape, and errors in defining centers undoubtedly increased. The extreme outer data points were usually so small in size that errors in position were again reduced. All pictures taken with low values of extracted ion current were difficult to read because of the large halos, faintness of data points, and irregular shapes of points.

Following the digitizing and interpolation process, the data were phase space analyzed by computer. This approach was used to allow reduction of all the data points on a given record, thus providing a measure of the accuracy of the analysis. The code first calculated the center of the beam from symmetry. The data points were then arranged by column and row to match their physical location as shown in Fig. 30. Position and divergence of each column and

TABLE VI

Picture No.	Arc Magnet Current (A)	Extractor Voltage (V)	Electron Trap Voltage (kV)	Transformer Current (mA)	Chamber Pressure (μ)	Repetition Rate (Sec^{-1})	Pulse Width (μsec)	Comments
1A	1.75	25.8	-10	48	98	15	100	"A" series, preliminary study, was phase-space analyzed, but not reported here (1A-10A).
2A	1.75	25.8	-10	48	98	15	100	
3A	1.75	27.0	-10	48	98	15	100	
4A	2.37	25.8	-10	48	98	15	100	
5A	1.75	25.8	-10	32	98	15	100	
6A								
7A	1.75	25.8	-10	44	98	15	100	"B" series, preliminary study, not analyzed here (1B-6B).
8A	1.75	25.8	-10	49	98	15	100	
9A	1.75	25.8	-10	50	98	15	100	
10A	1.75	25.8	-10	36	98	15	100	
1B	1.75	25.8	-10	10	120	15	100	
2B	1.75	25.8	-10	20	120	15	100	
3B	1.75	25.8	-10	28	120	15	100	Current parametric with 1.75 A arc magnet current and 25.8 extractor voltage. No. 1 contained bad data, was not analyzed. (1-8) Current parametric with 1.75 A arc magnet current and 27.0 extractor voltage. No. 16 contained bad data. (9-16)
4B	1.75	25.8	-10	32	120	15	100	
5B	1.75	25.8	-10	36	120	15	100	
6B	1.75	25.8	-10	40	120	15	100	
1	1.75	25.8	-10	10	120	15	100	
2	1.75	25.8	-10	20	120	15	100	
3	1.75	25.8	-10	28	120	15	100	
4	1.75	25.8	-10	32	120	15	100	
5	1.75	25.8	-10	36	120	15	100	
6	1.75	25.8	-10	40	120	15	100	
7	1.75	25.8	-10	44	120	15	100	
8	1.75	25.8	-10	48	120	15	100	
9	1.75	27.0	-10	48	120	15	100	
10	1.75	27.0	-10	44	120	15	100	
11	1.75	27.0	-10	40	120	15	100	
12	1.75	27.0	-10	36	120	15	100	
13	1.75	27.0	-10	32	120	15	100	No. 19 is a duplicate of No. 1. Current parametric with 2.60 A arc magnet current and 25.8 extractor voltage. No. 25 was doubled exposed. (20-27) Current parametric with 2.54 A arc magnet current and 27.0 extractor voltage. No. 35 was double exposed. (28-35) Wedge series; exposure times were varied from 5sec to 320sec. Nos. 36 and 37 have no grid; 38, 39 and 42 are duplicates; only 40 and 41 were analyzed. (36-42) No. 43 duplicate of No. 35.
14	1.75	27.0	-10	28	120	15	100	
15	1.75	27.0	-10	20	120	15	100	
16	1.75	27.0	-10	10	120	15	100	
17	2.50	25.8	-10	10	120	15	100	
18	2.6	25.8	-10	7	120	15	100	
19	1.7	25.8	-10	10	120	15	100	
20	2.6	25.8	-10	10	120	15	100	
21	2.6	25.8	-10	20	120	15	100	
22	2.6	25.8	-10	28	120	15	100	
23	2.6	25.8	-10	32	120	15	100	
24	2.6	25.8	-10	36	120	15	100	
25	2.60	25.8	-10	40	120	15	100	
26	2.60	25.8	-10	44	120	15	100	
27	2.60	25.8	-10	48	120	15	100	
28	2.54	27.0	-10	48	120	15	100	
29	2.54	27.0	-10	44	120	15	100	No. 43 duplicate of No. 35.
30	2.54	27.0	-10	40	110	15	100	
31	2.54	27.0	-10	36	110	15	100	
32	2.54	27.0	-10	32	110	15	100	
33	2.54	27.0	-10	28	110	15	100	
34	2.54	27.0	-10	20	110	15	100	
35	2.54	27.0	-10	10	110	15	100	
36	1.75	27.0	-10	48	120	15	100	
37	1.75	27.0	-10	48	120	15	100	
38	1.75	27.0	-10	48	120	15	100	
39	1.75	27.0	-10	48	120	15	100	
40	1.75	27.0	-10	48	130	15	100	
41	1.75	27.0	-10	48	130	15	100	
42	1.75	27.0	-10	48	140	15	100	
43	2.54	27.0	-10	12	110	15	100	

TABLE VI
(Continued)

Picture No.	Arc Magnet Current (A)	Extractor Voltage (V)	Electron Trap Voltage (kV)	Transformer Current (mA)	Chamber Pressure (μ)	Repetition Rate (Sec^{-1})	Pulse Width (μsec)	Comments
44	1.75	25.8	-10	10	110	120	10	Short pulse width series. Repetition rate was increased for photographic compensation. Nos. 44 and 53 contained bad data. (44-61)
45	1.75	25.8	-10	20	110	120	10	
46	1.75	25.8	-10	28	110	120	10	
47	1.75	25.8	-10	32	135	120	10	
48	1.75	25.8	-10	36	135	120	10	
49	1.75	25.8	-10	40	135	120	10	
50	1.75	25.8	-10	44	135	120	10	
51	1.75	25.8	-10	38	135	120	10	
52	1.75	25.8	-10	51	135	120	10	
53	1.75	25.8	-10	10	100	120	20	
54	1.75	25.8	-10	20	100	120	10	
55	1.75	25.8	-10	28	100	120	10	
56	1.75	25.8	-10	32	100	120	10	
57	1.75	25.8	-10	36	100	120	10	
58	1.75	25.8	-10	40	105	120	10	
59	1.75	25.8	-10	44	110	120	20	
60	1.75	25.8	-10	48	140	120	20	
61	1.75	25.8	-10	50	140	120	20	
62	1.75	25.8	-10	10	170	15	100	Current parametric with higher chamber pressure. (62-70)
63	1.75	25.8	-10	20	170	15	100	
64	1.75	25.8	-10	28	170	15	100	
65	1.75	25.8	-10	32	170	15	100	
66	1.75	25.8	-10	36	170	15	100	
67	1.75	25.8	-10	40	170	15	100	
68	1.75	25.8	-10	44	170	15	100	
69	1.75	25.8	-10	48	170	15	100	
70	1.75	25.8	-10	50.5	170	15	100	Various parametric studies with the electron trap at -10, -5, and 0 kV. No. 80 was double exposed; 84 is non-existent. (71-88)
71	1.75	25.8	-5	10	125	15	100	
72	1.75	25.8	-5	20	125	15	100	
73	1.75	25.8	-5	28	125	15	100	
74	1.75	25.8	-5	32	125	15	100	
75	1.75	25.8	-5	36	125	15	100	
76	1.75	25.8	-5	40	125	15	100	
77	1.75	25.8	-5	44	125	15	100	
78	1.75	25.8	-5	48	130	15	100	
79	2.60	25.8	-5	48	130	15	100	
80	2.60	25.8	-5	44	130	15	100	
81	2.60	25.8	-10	44	130	15	100	
82	2.60	25.8	-5	30	130	15	100	
83	1.75	25.8	-10	44	130	15	100	
84								
85	1.75	27.0	0	32	65	15	100	
86	1.75	27.0	0	40	65	15	100	
87	1.75	27.0	0	48	80			
88	1.75	27.0	-10	40	80	15	100	

row were then calculated differentially and plotted on film by an H or V (horizontal or vertical). The radius and radial divergence of the individual data points were next computed by taking the square root of the sum of the squares of the x-x' and y-y' data. These were plotted in the first quadrant with asterisks.

Figure 31 shows an example of the resulting phase space plots. The photograph analyzed is again picture No. 26, representing the standard operating condition. The scale is ± 20 mrad and ± 1.5 cm. As shown by the closeness of the lines marked horizontal and vertical, the beam phase space appears symmetric with respect to axial rotation. The narrow spread in the asterisk group illustrates the adequacy of the calculation and provides a measure of total error. Beam divergence was estimated from symmetry of the group extrapolated to the position of maximum extent. Visual inspection of Fig. 31 indicates an envelope with maximum size of 1.21 cm and divergence of 15.1 mrad. It is again emphasized that Fig. 31 gives no information regarding beam intensity. This must be obtained from plots such as Figs. 27 or 29.

The series of pictures 1-88 was analyzed in similar fashion. Figure 32 is a plot of divergence and size of the main body for the beams studied in this series. Data points are labeled by picture number.

Fig. 31. Phase space analysis of picture No. 26.

Figure 32 serves to illustrate the only strong correlation noted in this study: increasing column current produces a larger beam envelope and greater divergence. In Fig. 32 the extracted current ranges from 7 mA at the lower left-hand corner to 51 mA at the upper right. With few exceptions, data points for currents above 40 mA lie in a tightly clustered group between 15 and 17 mrad, roughly. These data points represent a wide range in the other operating parameters. Thus, it appears that the beam phase space is in some sense saturating at the upper current levels. The intensity measurements discussed in the previous section indicate that it may be possible to effect changes in the intensity profiles of the beam. However, Fig. 32 shows that the phase space envelope is basically unaffected by changes in operating parameters other than extracted current.

Some of the results of the principle parametric studies are shown graphically in Figs. 33-37. The small numbers associated with each data point represent the extracted ion currents.

Figure 33 indicates a slight correlation of phase space with arc magnet current at the higher extracted ion current end of the curve. Arc magnet current has been found to affect the phase space orientation slightly at EM1, and to a greater extent at EM2 and EM3. However, it is not known whether these effects are due to the slight change in the phase space envelope or to the density redistribution indicated by the intensity measurements. In any case, a slight improvement is found in running at the higher arc magnet current of 2.6 A. Figure 34 indicates a slight shift down and to the left for the lower extractor voltage. The operating point has been redefined to be 25.8 V. Figure 35 indicates that chamber pressure has almost no effect upon the beam phase space. Figure 36 illustrates the result of an experiment in which pulse width was reduced. Repetition rate was correspondingly increased to produce a comparable photographic image. There would seem to be a high correlation; however, the direction and magnitude of the shifts are such as to suggest a purely extracted ion current effect. That is, 10 usec encompasses the column current transient period, and thus has an average lower current than the steady-state portion of the pulse.

Fig. 32. Summary of pepper-pot data, Series 1-88.

Fig. 33. Beam phase space versus arc magnet current.

Fig. 34. Beam phase space versus extractor voltage.

Fig. 35. Beam phase space versus chamber pressure.

Fig. 36. Beam phase space versus pulse width.

Figure 37 reveals electron trap voltage to have little effect on beam phase space. As previously explained, the pepper-pot plate was biased to 150 V during these tests. The high electron retention of the plate allowed this experiment to be performed. Trap configuration has previously been noted to produce measurable phase space rotations at EMI. These would appear not to be due to an effect within the column.

All of the data taken with the pepper pot have been presented as analyzed, and represent beam properties at a position roughly 5 in. from the exit of the column. We chose to present the data in this way to avoid the possible ambiguity inherent in a transformation. However, to allow the possibility of making calculations beginning at the exit of the column, we have transformed the data representing the standard operating parameters and various extracted ion currents. These transformed data points are shown in Fig. 38. The calculations were done with a radially symmetric Kapchinsky-Vladimirsky code. Consideration was taken of the higher charge density of the H_2^+ species; due to the excellent biasing result, electron neutralization effects were neglected. The calculation over such a short distance should be accurate. Further, a transformation of a radially symmetric beam envelope

is not dependent upon the density distribution. The result is that the data point labeled 26, which represents the standard operating condition, has a size of ± 1.03 cm and a divergence of ± 14.6 mrad at the center line of the tenth electrode

The tails have been defined to have a phase space distinct from that of the main body of the beam. To shed more light on this phenomenon, an analysis was done of pictures 21 and 26 for those data points not within the main body phase space. The results are shown in Figs. 39 and 40. The phase space region previously designated as main body is shown as the shaded area. The extremities of this area define the beam envelope. The tails shown represent the outer loci of points in x-x' or y-y' space and may reflect a radial distribution in phase space. Figure 39 (picture No. 26) represents the design operating condition, while Fig. 40 (picture No. 21) illustrates the result for a lower extracted current of 20 mA.

Previous measurements at EMI resulted in observations of beam steering, or displacement of the beam off axis, as a function of extracted ion current. In an attempt to find the source of this phenomenon, a record was kept of the calculated beam centers obtained from the pepper-pot photographs. These data points were plotted versus

Fig. 37. Beam phase space versus electron trap voltage.

Fig. 38. Standard operating condition phase space transformed to the exit of the column.

various operating parameters, including extracted current. The results show that beam position cannot be correlated with any of the operating parameters. Fluctuations appear random and probably reflect the use of a symmetry calculation in determining the beam center. In other words, there is no beam steering effect, at least up to this point along the beam line. Further, the center of the beam seems to coincide very closely with the axis of the accelerating column previously determined by jig transit measurements.

Fig. 39. Transverse phase space for picture No. 26.

Fig. 40. Transverse phase space for picture No. 21.

APPENDIX

QUARTZ PLATE TEMPERATURE CALCULATIONS

During the tests conducted with the quartz plate viewing screens, it was observed that, at high power levels, the light output from the quartz decreased over a period of several seconds. These observations were first made visually and later confirmed using the vidicon intensity scanner. It was also observed that, as the pulse length was increased to 500 usec, the central black region in the beam progressively increased until finally a bright spot was observed in the center of the beam. Visual observation of the screen confirmed that the quartz was glowing red hot at this point, and subsequent inspection of the screen showed that the quartz had been partially eaten away. These observations suggest that there is significant heating of the quartz plate during the beam pulse, and that the apparent hollow structures at low current may be due to decreased fluorescence of the quartz. To investigate this, calculations have been made of the temperature rise at the surface of the quartz. No data, except the qualitative observation of decreased light output at higher beam power, have been found to confirm the decrease in fluorescence of the quartz with temperature.

Estimates of temperature rise in the quartz can be obtained by assuming the quartz behaves as a

semi-infinite solid with radiation impinging on its front surface. Since the range of 750 kV protons is only several microns in quartz, this is a valid assumption during any one beam pulse. An independent calculation must be done to determine the average temperature rise of the plate.

Using the results for this model,⁶ we have

$$\Delta T = \frac{2 F_0}{K} \sqrt{\frac{\kappa t}{\pi}}$$

ΔT - Temperature rise at the surface of the solid

F_0 - Thermal flux per unit area per unit time

K - Thermal conductivity

$\kappa = \frac{K}{\rho c}$ - Thermal diffusivity

t - Time after the heating at rate F_0 starts.

For quartz, we have

$K = 0.03 \text{ cal/cm-sec, } ^\circ\text{C}$

$\rho = 2.65 \text{ g/cm}^3$

$c = 0.18 \text{ cal/g-}^\circ\text{C-}$

Thus, $\kappa = 0.063 \text{ cm}^2/\text{sec}$.

The results of the surface heating for 20-usec and 100-usec beam pulses are tabulated in Table A.I. We note that the maximum excursion during a beam

TABLE A.I
QUARTZ PLATE TEMPERATURE EXCURSION CALCULATIONS

I	R	Area	Power	F_0	F_0	$\Delta T(20 \text{ usec})$	$\Delta T(100 \text{ usec})$
<u>mA</u>	<u>cm</u>	<u>cm</u>	<u>kW</u>	<u>kW/cm</u>	<u>kcal/cm-sec</u>	<u>°C</u>	<u>°C</u>
2.0	0.25	0.20	1.5	7.65	1.83	73	163
6.0	0.35	0.39	4.5	11.7	2.80	118	264
10.0	0.58	1.06	7.5	7.1	1.70	72	160
20.0	0.92	2.68	15.0	5.6	1.34	57	127
30.0	1.34	5.65	22.5	4.0	0.96	41	91
40.0	1.63	8.35	30.0	3.6	0.86	36	81
44.0	1.69	8.98	33.0	3.7	0.88	37	83
46.0	1.77	9.83	34.5	3.5	0.84	36	80

pulse occurs at currents near 6 mA because the specific thermal flux becomes large as the main central spot size of the beam decreases.

In order to estimate the average temperature rise, boundary conditions are imposed by assuming the perimeter plate to be maintained at a constant temperature T_0 . The plate thickness is sufficiently small compared to the diameter so that the heat flow can be considered radial. The entire central region of the quartz out to beam radius r_0 is taken to be a uniform temperature T_a . For the experiments carried out in these tests, a pulse repetition rate of 15 pps was used; thus the duty factor for the 20- μ sec case is 0.3×10^{-3} and for the 100- μ sec case is 1.5×10^{-3} . The average power input H to the quartz plate is then simply the product of the instantaneous beam power times the appropriate duty factor. We then equate the average power input to

the radial heat flow in the unheated region. The result is

$$-KA \frac{dT}{dr} = H \quad \begin{aligned} H &= (\text{Power}) \times (\text{Duty Factor}) \\ R_0 &= 4.45 \text{ cm} \\ T &= 0.635 \text{ cm} \end{aligned}$$

$$-dT = \frac{H}{KA} dr$$

$$-\int_{T_0}^T dT = \int_r^{R_0} \frac{H}{2\pi Kt} \frac{dr}{r} = \frac{H}{2\pi Kt} \ln \left(\frac{R_0}{r} \right)$$

$$(T - T_0) = \frac{H}{2 Kt} \ln \left(\frac{R_0}{r} \right)$$

Thus, the peak temperature at the surface of the quartz plate is given approximately by the sum of the two calculations. Results are tabulated in Table A.II. At equilibrium, the thermal profile of the front surface of the quartz is shown in Fig. A.1.

TABLE A.II
AVERAGE TEMPERATURE RISE IN QUARTZ PLATE

I	R	$\ln(R_0/R)$	Power	H(20 μ sec)	T_{avg} (20 μ sec)	H(100 μ sec)	T_{avg} (100 μ sec)
mA	cm		kcal/sec	cal/sec	$^{\circ}\text{C}$	cal/sec	$^{\circ}\text{C}$
2.0	0.25	2.88	0.36	0.11	1.63	0.55	8.5
6.0	0.35	2.54	1.08	0.32	4.31	1.60	21.5
10.0	0.58	2.04	1.79	0.54	9.2	2.58	44.0
20.0	0.92	1.57	3.58	1.07	14.0	5.37	70.5
30.0	1.34	1.20	5.36	1.60	16.0	8.05	80.5
40.0	1.63	1.0	7.18	2.15	17.9	10.8	90.1
44.0	1.69	0.96	7.90	2.37	19.0	11.8	94.5
46.0	1.77	0.92	8.27	2.48	18.3	12.4	91.5

The characteristic time for heat transfer to occur in the quartz plate can be estimated by calculating the time required for the back surface of the plate to rise to 1/2 its average steady state temperature. Using the results of the theory⁷ for a semi-infinite solid, one obtains

$$\frac{x}{2\sqrt{Kt}} = 0.477 \quad x = 0.635 \text{ cm}$$

$$t_{1/2} = \frac{x^2}{4K(0.477)^2}$$

$$t_{1/2} = 7.0 \text{ sec for this quartz plate.}$$

Fig. A.1. Temperature of the front surface of the quartz plate.

This is in qualitative agreement with experiment in that there was a decreased light output over several seconds when the pulse length was increased.

Results of these calculations are shown in Table A.III. Maximum temperature at the front surface is relatively independent of the beam current, but the maximum excursion is much higher for the low current beams. At the higher currents, the entire

TABLE A.III

SURFACE TEMPERATURE RISE IN THE QUARTZ PLATE

20μsec Pulses				100μsec Pulses		
I	T _{avg}	ΔT	T _{max}	T _{avg}	ΔT	T _{max}
mA	°C	°C	°C	°C	°C	°C
2	1.7	73	74.7	9	163	172
6	4.5	118	122.3	22	264	286
10	9.2	71.5	80.7	44	160	204
20	14.0	56.8	70.8	71	127	198
30	16.0	40.5	56.5	81	91	172
40	17.9	36.4	54.3	90	81	171
44	19.0	37.1	56.1	95	83	178
46	18.3	35.6	53.9	92	82	182

plate becomes hot but there is a much smaller temperature variation during the beam pulse. Since it is believed that, above a certain point, light output decreases with increasing temperature, it would appear that the apparent hollows that occur at low beam currents are due at least in part to the high temperature excursion that occurs during the beam pulse, and that at the higher currents the uniform decreases in light output which is observed over the entire beam spot can be attributed to the average temperature rise.

Additional photographs were taken for which only the pulse length was varied. In Figs. A.2 and A.3 we see photographs of beams of 40- and 42-mA current. A hot spot is observed at low pulse length which becomes hollow at higher pulse lengths, presumably because of the heating of the quartz. In Figs. A.4 and A.5, we see a 6-mA and 10-mA cross-sections, respectively, together with intensity profiles from the vidicon intensity scanner. The central hollow is also believed to be due to the large temperature excursion of the plate rather than a time dependent hollow in the beam. The ring structure and square appearance of the central hollow are still not understood.

For the pepper-pot work, the temperature excursions are much smaller. The average heating effect is negligible. The peak heating is reduced by the divergence of the beam. A typical spot size of 0.010 in. results from a 0.002-in. hole, thus giving a reduction in intensity of 25. Hence a 10°C maximum temperature rise would be expected.

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10 μsec

20 μsec

40 μsec

80 μsec

100 μsec

160 μsec

Fig. A.2. Beam cross section with arc magnet current 1.50 A and beam current 40 mA.

10 μsec

20 μsec

40 μsec

80 μsec

100 μsec

160 μsec

Fig. A.3. Beam cross section with arc magnet current 1.50 A and beam current 42 mA.

20 μsec PULSE LENGTH

60 μsec PULSE LENGTH

100 μsec PULSE LENGTH

BEAM CURRENT - 6 mA
ARC MAGNET CURRENT - 1.5 AMPS

Fig. A.4. Beam cross sections 16 in. from exit of accelerating column.

20 μsec PULSE LENGTH

60 μsec PULSE LENGTH

100 μsec PULSE LENGTH

BEAM CURRENT-10 mA
ARC MAGNET CURRENT-1.5 AMPS

Fig. A.5. Beam cross sections 16 in. from exit of accelerating column.

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