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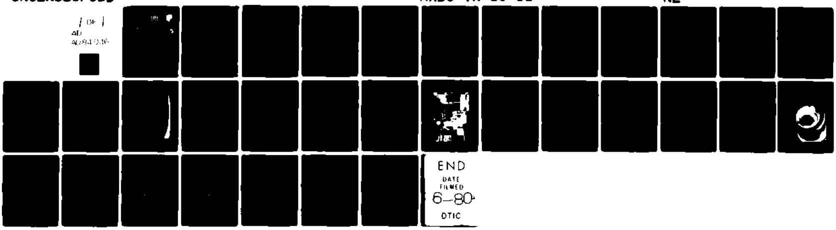
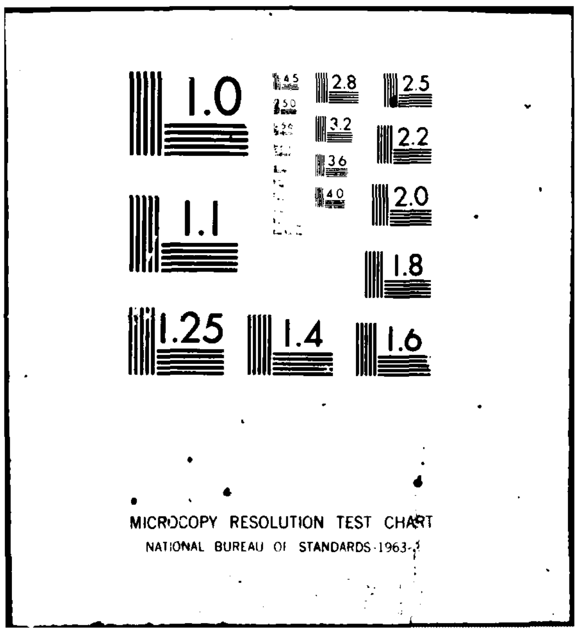
UNCLASSIFIED RADC-TR-80-51 NL

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RADC-TR-80-51
Final Technical Report
March 1980

CONTIGUOUS GRIDDED GUN DEVELOPMENT PROGRAM

Varian Associates

ROME AIR DEVELOPMENT CENTER
Air Force Systems Command
Griffiss Air Force Base, New York 13441

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RADC-TR-80-51 has been reviewed and is approved for publication.

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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: RADC-TR-80-51

2. GOVT ACCESSION NO.: AD-A084 046

3. RECIPIENT'S CATALOG NUMBER:

4. TITLE (and Subtitle): CONTIGUOUS GRIDDED GUN DEVELOPMENT PROGRAM

5. TYPE OF REPORT & PERIOD COVERED: Final Technical Rep[redacted]t, Mar[redacted] 1978 — Aug[redacted] 1979

6. PERFORMING ORG. REPORT NUMBER: N/A

7. AUTHOR(s): Glen Huffman

8. CONTRACT OR GRANT NUMBER(s): F30602-78-C-0123

9. PERFORMING ORGANIZATION NAME AND ADDRESS:
Varian Associates, Inc.
611 Hansen Way
Palo Alto CA 94303

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS:
62702F
45061216

11. CONTROLLING OFFICE NAME AND ADDRESS:
Rome Air Development Center (OCTP)
Griffiss AFB NY 13441

12. REPORT DATE: Mar[redacted]80

13. NUMBER OF PAGES: 33

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): Same

15. SECURITY CLASS. (of this report): UNCLASSIFIED

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE: N/A

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

Same

18. SUPPLEMENTARY NOTES

RADC Project Engineer: Albert F. Morreall (OCTP)

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Contiguous Gridded Gun
linear beam tubes
beam analyzer
Low Control Grid Interception
beam diameter
voltage
current
perveance
Grid Operating Voltage
Cathode Emission Density
High Voltage Gradients
Tungsten Matrix Cathode

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A gridded gun, suitable for operating megawatt level linear beam tubes, has been designed and tested at lower levels in a beam analyzer. The new gun features a shadow grid in contact with the cathode surface. A major goal was to achieve low control grid interception.

Guns with contiguous grid systems are in common use in low and medium power tubes. The purpose of this program was to extend existing lower

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power gridded gun technology to the megawatt level.

The basic gun parameters including beam diameter, voltage, current, perveance and grid operating voltage are all quite conservative and readily achievable in an 83 kV gun.

The most critical requirement was that the maximum outer diameter of the gun assembly not exceed 5.48 inches. This limit forced a compromise between cathode emission density and high voltage gradients and dictated the use of a tungsten matrix cathode.

A scale model gun was built and tested in a beam analyzer. After modification to the design, a full-scale gun was built and also tested in the beam analyzer.

Extrapolations from the beam analyzer test data show that the gun should meet all performance objectives at full power except for heater power and grid bias voltage. The intercepted control grid current cannot be accurately estimated for full power operation, but it is believed that it will be less than the 40 milliamps specified.

The next step is to install the full-scale gun on an actual tube and evaluate performance.

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EVALUATION

The purpose of this effort was to demonstrate the feasibility of extending the contiguous shadow grid gun technology to the megawatt level for incorporation in devices such as the RADC "High Efficiency Klystron/TWT Hybrid" developed under Contract F30602-76-C-0130. Scaling to other tubes would of course be a relatively straightforward task.

Among the many advantages realized from this approach will be improved beam quality, lower cost and since the design is less fragile, improved reliability and life.

The overall success of this effort indicates that the evaluation of this gun in an actual high power tube is warranted. This work is relevant to TPO 4B as it supports the development of broadband high power tubes for tactical application.

Albert F. Morreall

ALBERT F. MORREALL
Project Engineer

I. INTRODUCTION

The objective of this effort was to develop a gridded gun for a megawatt S-band linear beam amplifier. A major goal was to achieve low control grid interception in a gridded gun which has the shadow grid in contact with the cathode surface.

Gridded guns have been available for S-band megawatt level tubes since 1970. In all of these guns the shadow grid is located a short distance in front of the cathode. Great care is taken to keep the shadow grid from touching the cathode. Although this type of grid arrangement works satisfactorily, it has shortcomings. Locating the shadow grid in front of the cathode causes over-focusing of the individual beamlets as they leave the cathode surface. The resulting electron cross-overs degrade the beam optics and increase beam noise. These problems are eliminated when the shadow grid is placed directly in contact with the cathode because the grid profile can be shaped to properly focus the electrons as they leave the cathode surface.

From a mechanical point of view, the requirement to precisely position the shadow grid a few mils in front of the cathode increases fabrication costs and decreases reliability.

For the reasons cited above, gridded guns having the shadow grid in contact with the cathode are in common use in low and medium power linear beam tubes. The purpose of this program was to extend the existing lower power gridded gun technology to the megawatt level.

II. STATEMENT OF WORK AND TECHNICAL REQUIREMENTS

A. SCOPE

An improved gridded electron gun will be designed, built, and evaluated. The gun will have the shadow grid in contact with the cathode. A full-scale model of the gun capable of operating a megawatt level tube will be built and evaluated in an appropriate beam analyzer. Incorporation of this gun in an actual tube is not required.

B. TECHNICAL REQUIREMENTS

The objective specifications for the contiguous gridded gun are shown in Table I.

C. TEST AND EVALUATION

The gun shall be evaluated by the contractor in a suitable beam tester to determine performance with and without magnetic focusing. Tests will be made to determine the quality of the beam as well as the degree of compliance with the specifications in Table I.

III. DISCUSSION OF DESIGN TRADE-OFFS

The basic electronic parameters chosen for the contiguous gridded gun are quite reasonable. The beam diameter, voltage, current, and perveance, as well as the grid operating voltages, are readily achievable in an 83 kV gun. The challenge in designing this gun came from mechanical restraints placed upon it. The two most critical mechanical parameters are: first, the shadow grid must be in contact with the cathode and second, the overall OD of the gun package must be no more than 5 1/8 inches.

Table I
Contiguous Gridded Gun Specifications

1 - Type:
Shadow grid with masking grid contacting cathode.

2 - Beam Voltage: 83 kV

3 - Beam current: 38.3 A

4 - Beam perveance: 1.6×10^{-6}

5 - Heater voltage: 13 Vdc

6 - Heater current: 11.5 A

7 - Heater power: 150 W max

8 - Gun diameter: 5 1/8 inches maximum OD

9 - Grid voltage: 3100 V max for turn-on

10 - Grid bias: -950 V max

11 - Peak control grid interception: 0.040 A objective

12 - Beam tunnel diameter: 0.625 inches objective

Placing a properly shaped shadow grid directly on the cathode reduces electron cross-over and improves the optics of the individual beamlets in the grid region. However, the improved optics in the grid region result in the individual beamlets passing closer to the control grid, increasing the possibility of grid interception. Also, in the contiguous grid system, the operating temperature of the shadow grid will be higher, thus, making it a potential source of emitted electrons which will be intercepted by the control grid. Both of these problems, however, can be overcome.

Adequate clearance between the control grid and the individual beamlets can be obtained by careful design of the grid system. In particular, with the shadow grid located on the cathode, the profile of this grid is critical for establishing the initial electron trajectories. If the proper profile is chosen for the shadow grid, low grid interception will result.

The possibility of emission from the shadow grid can be eliminated through the use of a non-emissive coating (zirconium).

The maximum limits of 5 1/8 inches for the gun OD and 150 watts for the heater power create a design dilemma. These limits reflect the desire to have this new gun fit an existing system which now uses a klystron having an oxide coated type of cathode. But the unusually small OD for a high voltage, high current gun limits the cathode diameter and forces a trade-off between cathode diameter (emission density) and cathode-to-tube body spacings (voltage gradients). Cathode emission density is important because the gun should be capable of long pulse (greater than 100 microseconds) operation. Voltage gradients are important because the gun must operate reliably with the 83 kV applied continuously. The dilemma is that within the allowable diameter, the oxide coated cathode, which will meet the heater power limit, is marginal for the long pulse mode, while an impregnated tungsten matrix cathode, which can handle the long pulses, cannot meet the heater power specification. The problem is presented quantitatively in Table II, which compares the parameters of a tungsten matrix cathode with those of an oxide cathode chosen to have reasonable emission density. The peak voltage gradient of 300 volts per mil shown for the oxide cathode is unacceptable, while the value of 260 volts per mil for the type M cathode is marginally acceptable. An added benefit of the tungsten matrix type cathode is that its smaller diameter yields a lower area convergence ratio which makes the basic gun design easier.

In view of the trade-offs involved, the choice was made rather easily in favor of the tungsten matrix type cathode. It was felt that facing a cathode heater specification problem was less serious than facing a long pulse or high voltage arcing problem.

Table II
Comparison of Gun Parameters

	Type M Cathode	Oxide Cathode
Cathode Diameter (inches)	1.8	2.3
Cathode Area (cm^2)	16.4	26.8
Cathode Loading (A/cm^2) Assumes 0.75 grid transparency	3.1	1.9
Heater power ($watts/cm^2$)	14.0	6.0
Peak Voltage Gradient on Focus Electrode (V/mil)	~ 260	~ 300
Beam diameter (inches)	0.417	0.417
Area convergence	18.6	30.4

IV. COMPUTER-AIDED DESIGN RESULTS

The first step in any gun design is to develop paper designs using the computer with electron optics codes. In this case, design of the basic diode gun presented no problems since the perveance and convergence requirements were modest. In such cases, the computer results are quite accurate. A sample computer print-out of the basic gun is shown in Figure 1. Several design iterations were required to achieve the desired perveance, beam diameter and beam laminarity.

Next, the high voltage gradients were studied. In Figure 1, the maximum voltage gradients occur, not at the very tip of the focus electrode, but at the outer corner of the tip nearest the outer tube envelope.

The gradient problem was studied in greater detail using a simple Laplace computer code, which avoids the time-consuming electron optics calculations. An example of the Laplace results is shown in Figure 2. The maximum gradient shown in Figure 2 of 264 volts per mil is marginal for reliable operation. However, since this maximum occurs at a point far from the beam edge, modifications were made to the focus electrode shape to reduce the gradient to values below 250 volts per mil (the maximum acceptable value for reliable operation).

A more interesting task was the design of the grid system. The grid design chosen wa a radial vane structure having 72 cells in four rings surrounding a central aperture. Figure 3 is a sketch of the grid structure. After the basic grid pattern was worked out, the computer was used to determine the grid dimensions and spacings. This was done by using our electron optics codes to study half a single cell, as shown in Figure 4. In the figure, note the tapered shape of the shadow grid which is in contact with the cathode surface. The angle of the taper was chosen to provide near laminar flow of the edge electrons and adequate clearance between each beamlet and the control grid. For this reason, the grid in contact with the cathode is often called the focus grid, while the grid controlling the beam current is called the control grid. A special cross-sectional shape for the control grid is not required.

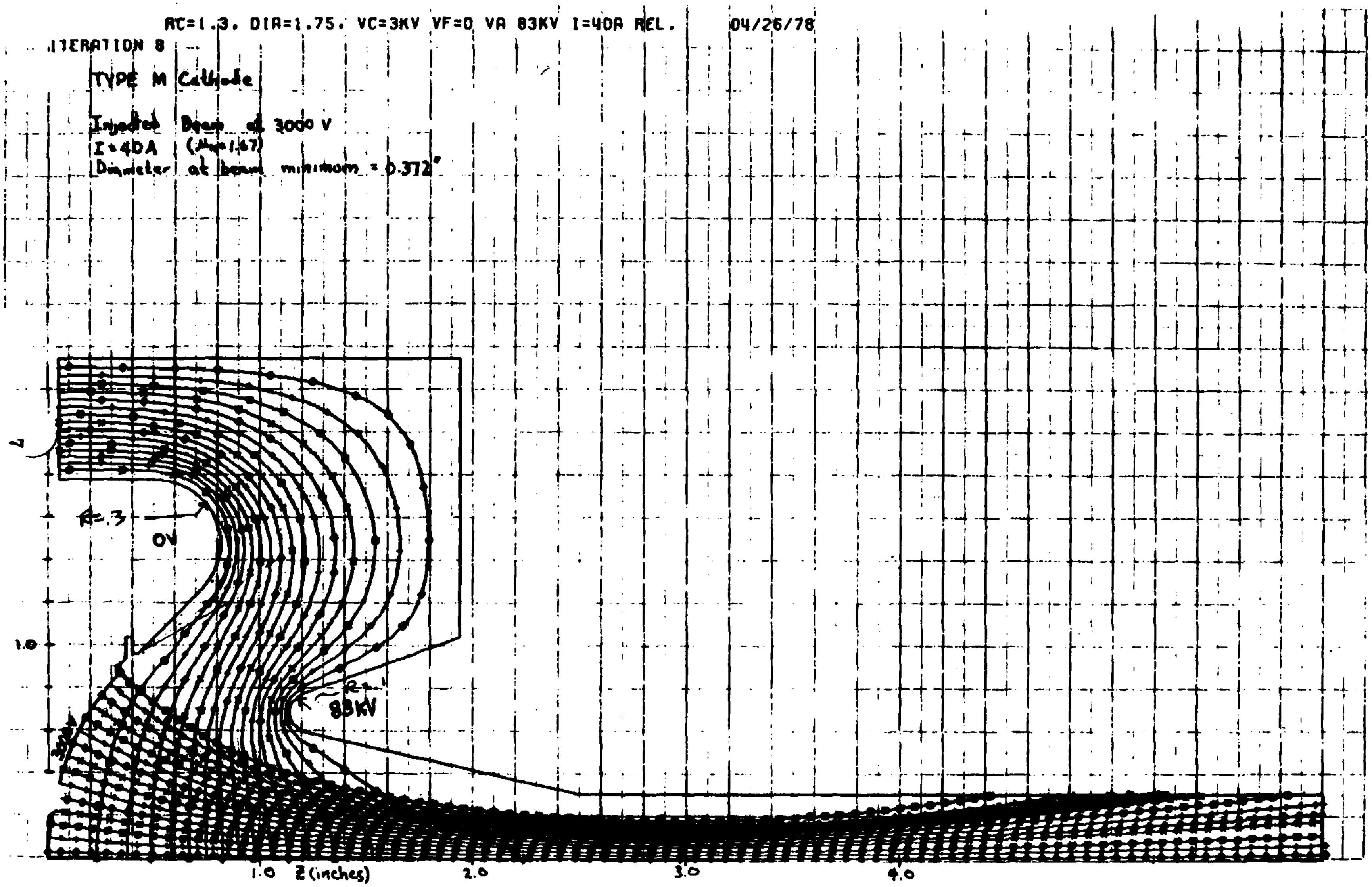

FIGURE 1. COMPUTER PRINTOUT OF THE BASIC GUN

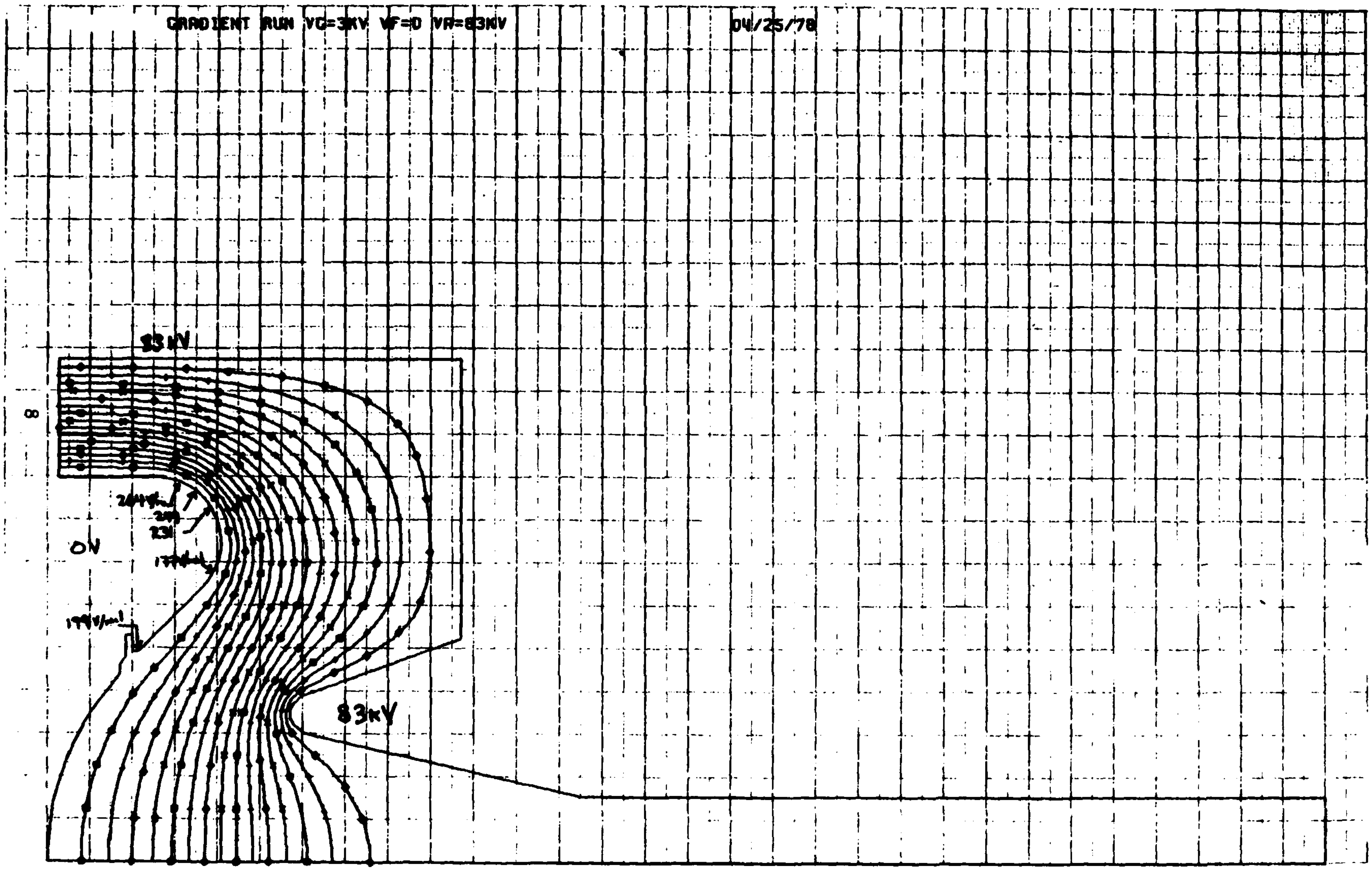

FIGURE 2. LAPLACE GRADIENT DATA

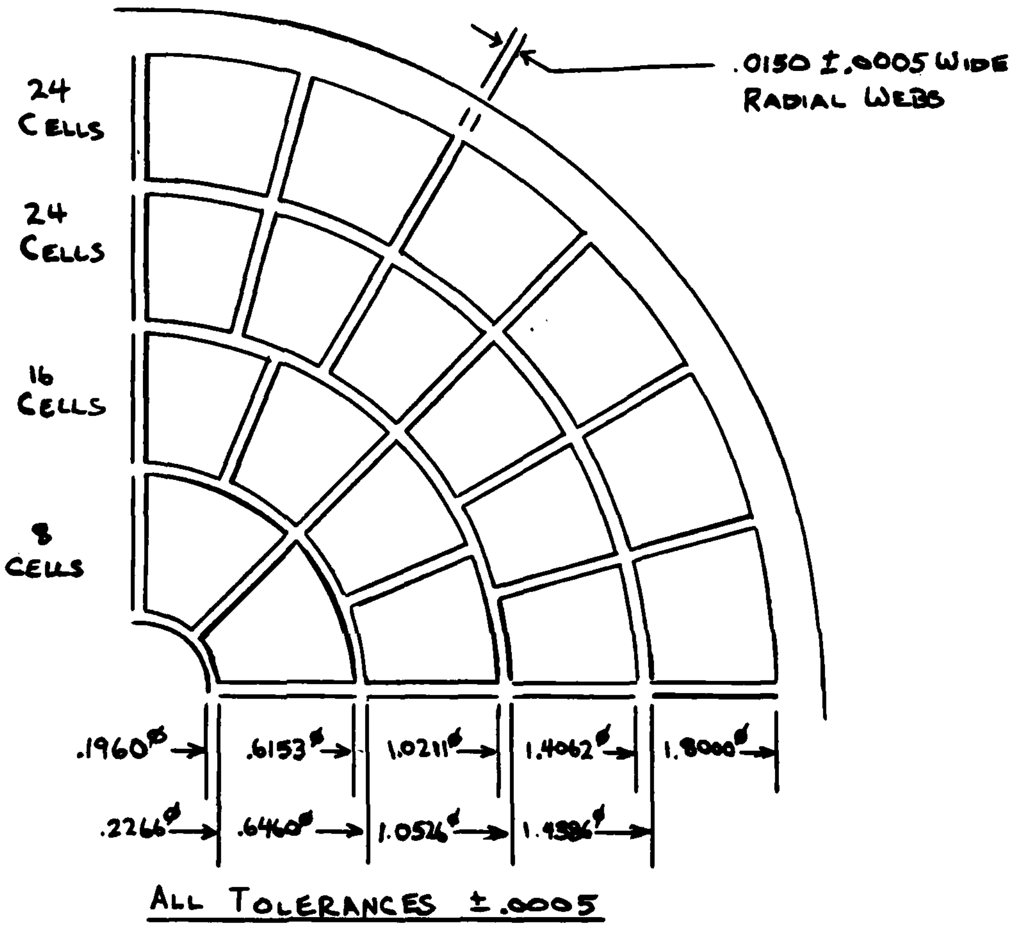

FIGURE 3. GRID STRUCTURE

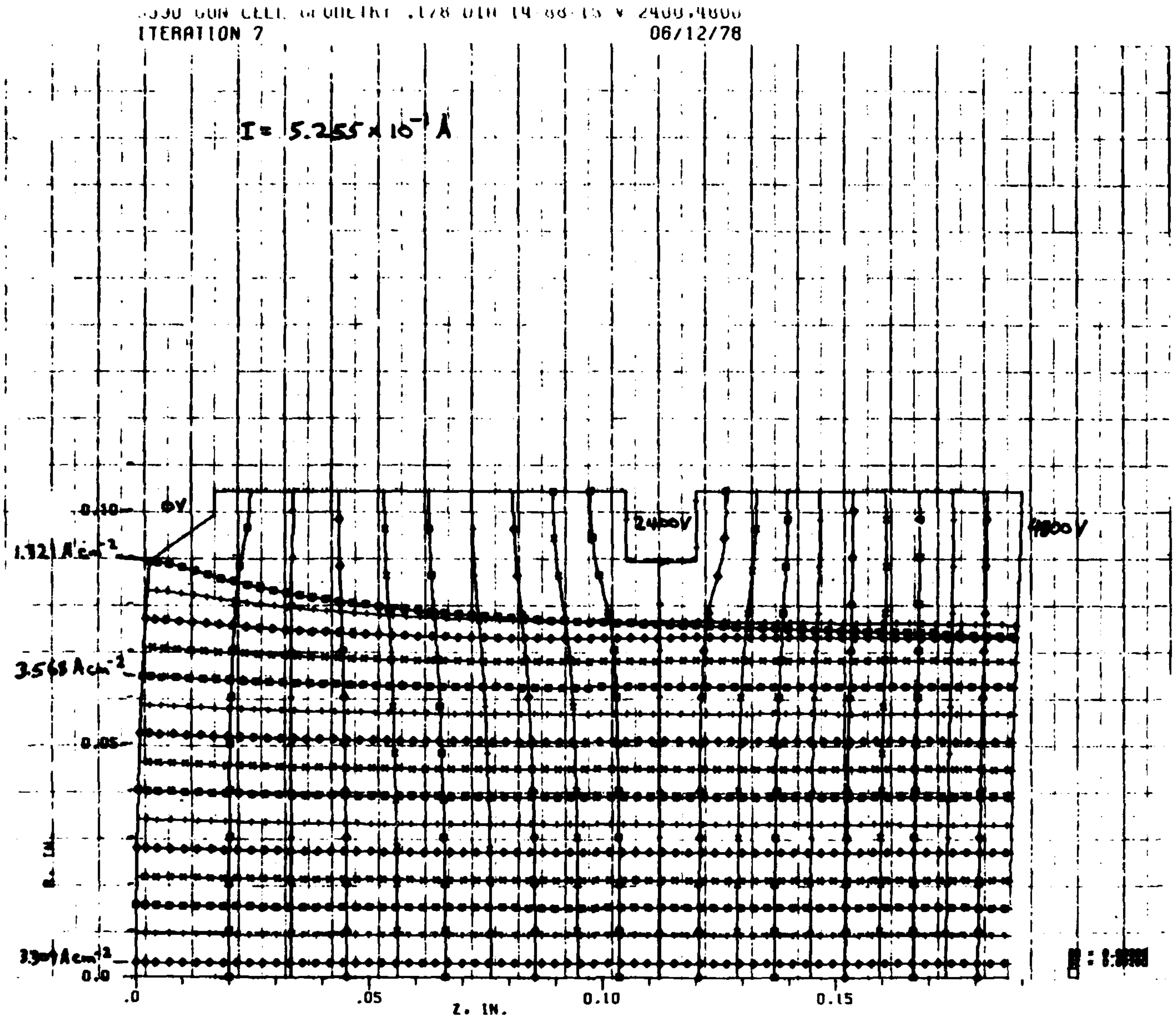

FIGURE 4. COMPUTER PRINTOUT OF ONE–HALF GRID CELL

V. SCALE MODEL GUN

The next step in the design procedure was to build and test a scale model gun in a beam analyzer. The purpose of this step was to check the validity of the paper design and make modifications as required to achieve the desired performance. With the exception of the focus electrode and anode, the scale model gun was assembled from existing parts, hence this step is a cost-effective method for refining the gun design before building the full-scale version.

Figure 5 is a picture of one of Varian's beam analyzers. In this unit, the electron beam is directed toward a target plate. A Faraday cup for measuring current is located behind the target. A tiny hole in the target plate admits a sample of beam current to the Faraday cup. The target assembly is mounted on a mechanism which provides precise three-axis motion. As the target moves across the beam, the Faraday cup samples the beam density and these data are fed to an x-y recorder. The result is a plot showing the current density profile across the beam. A series of these profiles taken along the axis of the beam reveal the characteristics of the beam.

The current density profiles for the scale model gun are shown in Figure 6. In this case, the beam profile is satisfactory, laminarity as indicated by the similarity of each profile is good, and the diameter is nearly correct but slightly large for scaling to the 0.625-inch diameter beam tunnel. A modification was made to the focus electrode to reduce the beam diameter slightly in the full-scale model gun.

In the scale model gun, a control grid voltage of only 84 volts was required to achieve the desired microperveance 1.5 beam at 6 kV. The 84 volt grid drive at the 6 kV level translates to approximately 1160 volts at the 63 kV operating level. The desired grid drive voltage range for the full-scale gun is 2400 to 2600 volts. Therefore, the grid drive voltage of the scale model gun was low by a factor of approximately 2. In the full-scale gun, the spacing between the control grid and the cathode was increased to raise the required grid drive voltage level.

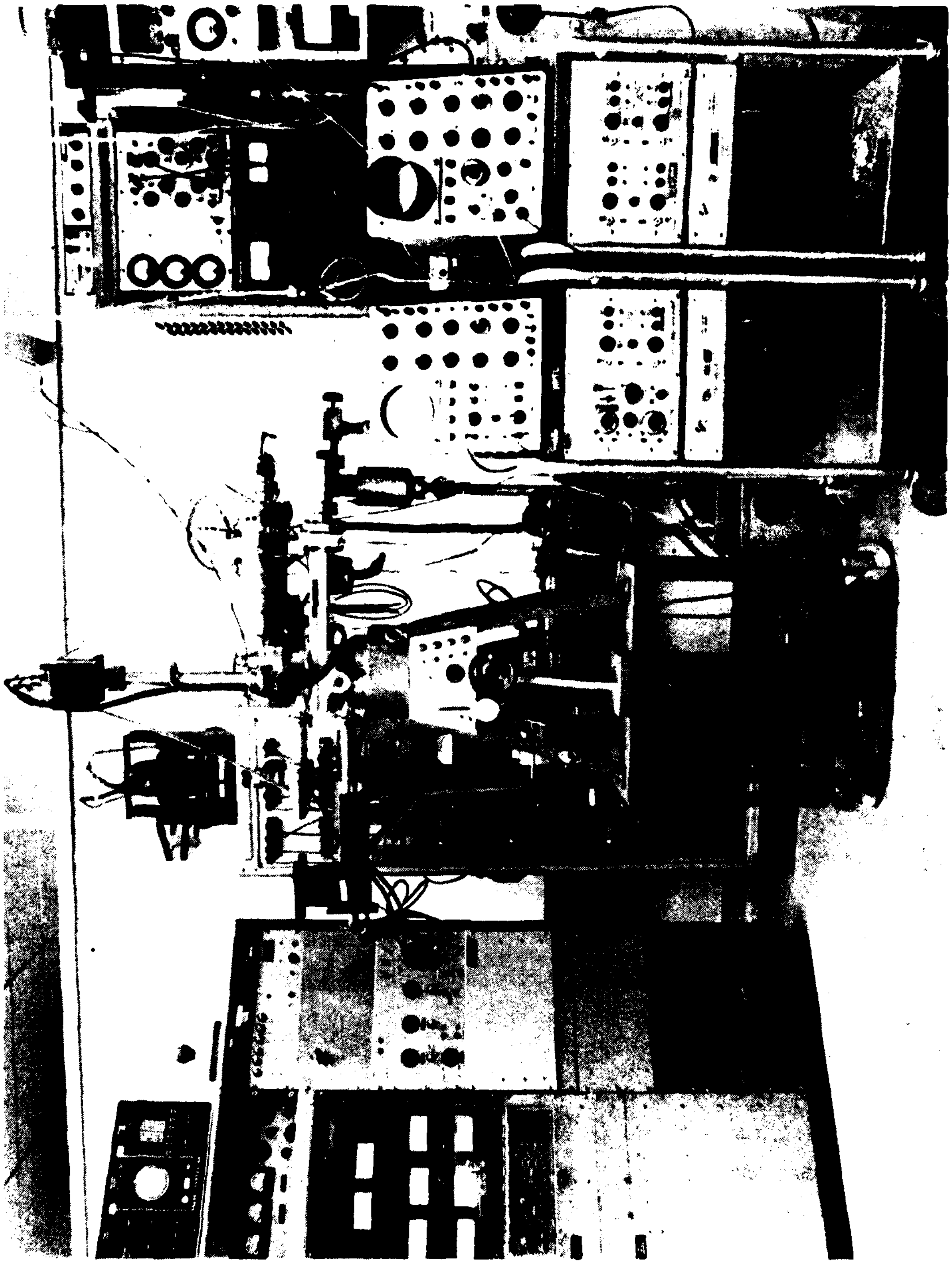

FIGURE 5. BEAM ANALYZER

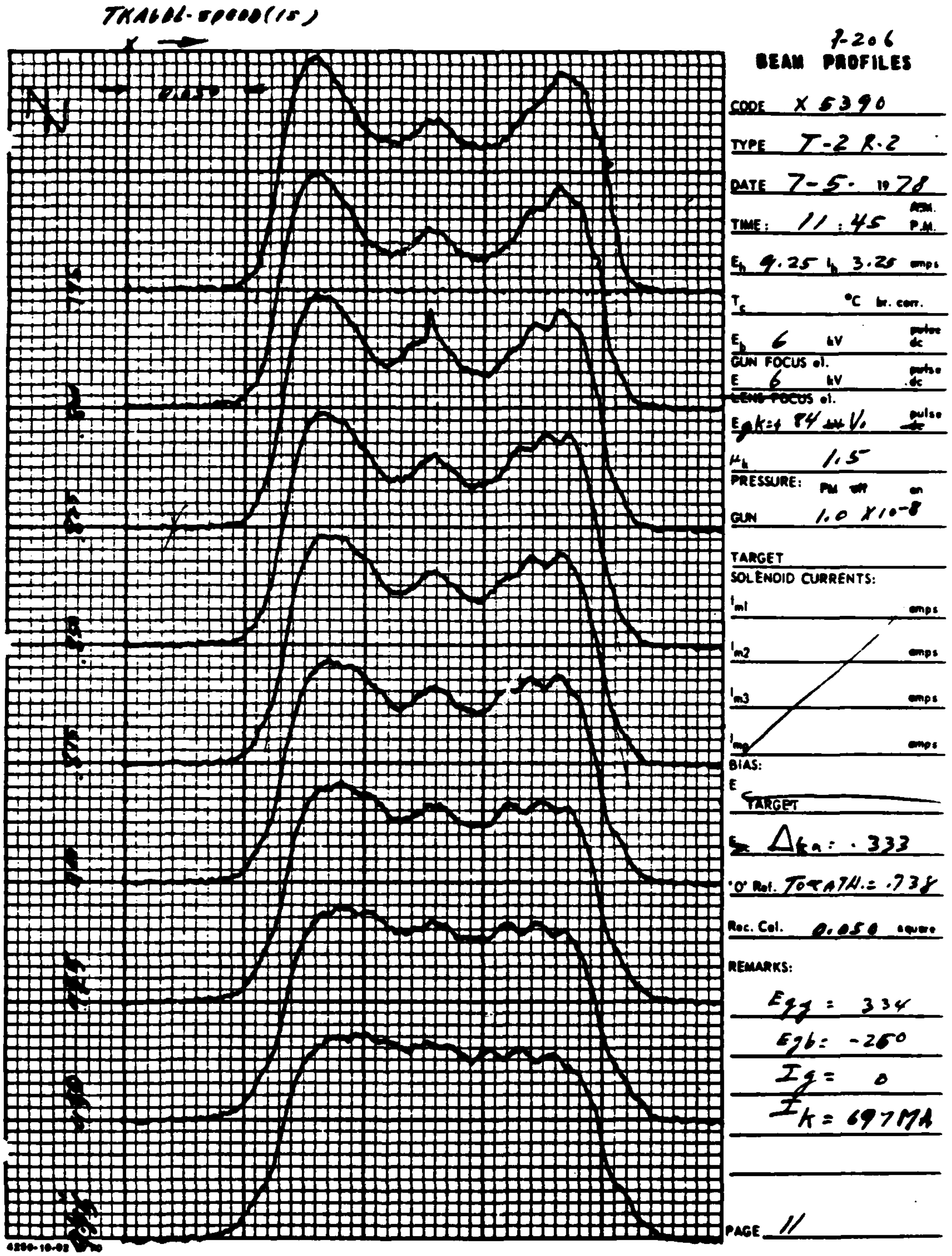

FIGURE 6. CURRENT DENSITY PROFILES FOR SCALE MODEL GUN

VI. MECHANICAL DESIGN OF FULL-SCALE GUN

The 5 1/8 inch limit on the overall gun diameter made it necessary to design entirely new high voltage ceramic insulator and cathode support assemblies for the full-scale gun. A sketch of the total full-scale gun assembly is shown in Figure 7. The gun is attached to the tube body by the weld flange located near the body end of the high voltage seal. The high voltage ceramic insulator was made 4.3 inches long to comply with the safe standard of 20 volts per mil maximum voltage gradient along non-vacuum insulator surfaces.

The pedestal supporting the cathode-grid-focus electrode assembly is made of copper and is the primary path for heat transfer to the outside environment. The external corona ring bolted to the base of the cathode pedestal is a heat radiator and requires either liquid or forced gas cooling.

The cathode heater is a non-inductive toroidal winding captured between ceramic rings. Multiple heat shields are used to improve heater efficiency. The heater power required by this cathode package was calculated to be 220 watts.

The grid support structure was designed to be thermally compensating so that the cathode-to-control grid spacing would remain constant with changes in cathode temperature. To achieve this condition, the grid support cylinder was made of high thermal expansion 404 Monel. To mate this material with the low expansion molybdenum grid ring, it was necessary to cut 36 slots in the Monel cylinder to provide fingers with sufficient flexibility to absorb the differences in thermal expansion.

A calculation of the operating temperature of the control grid was made using the following assumptions:

1. Temperature at the base of the cathode pedestal (corona ring) was $200^{\circ}C$.

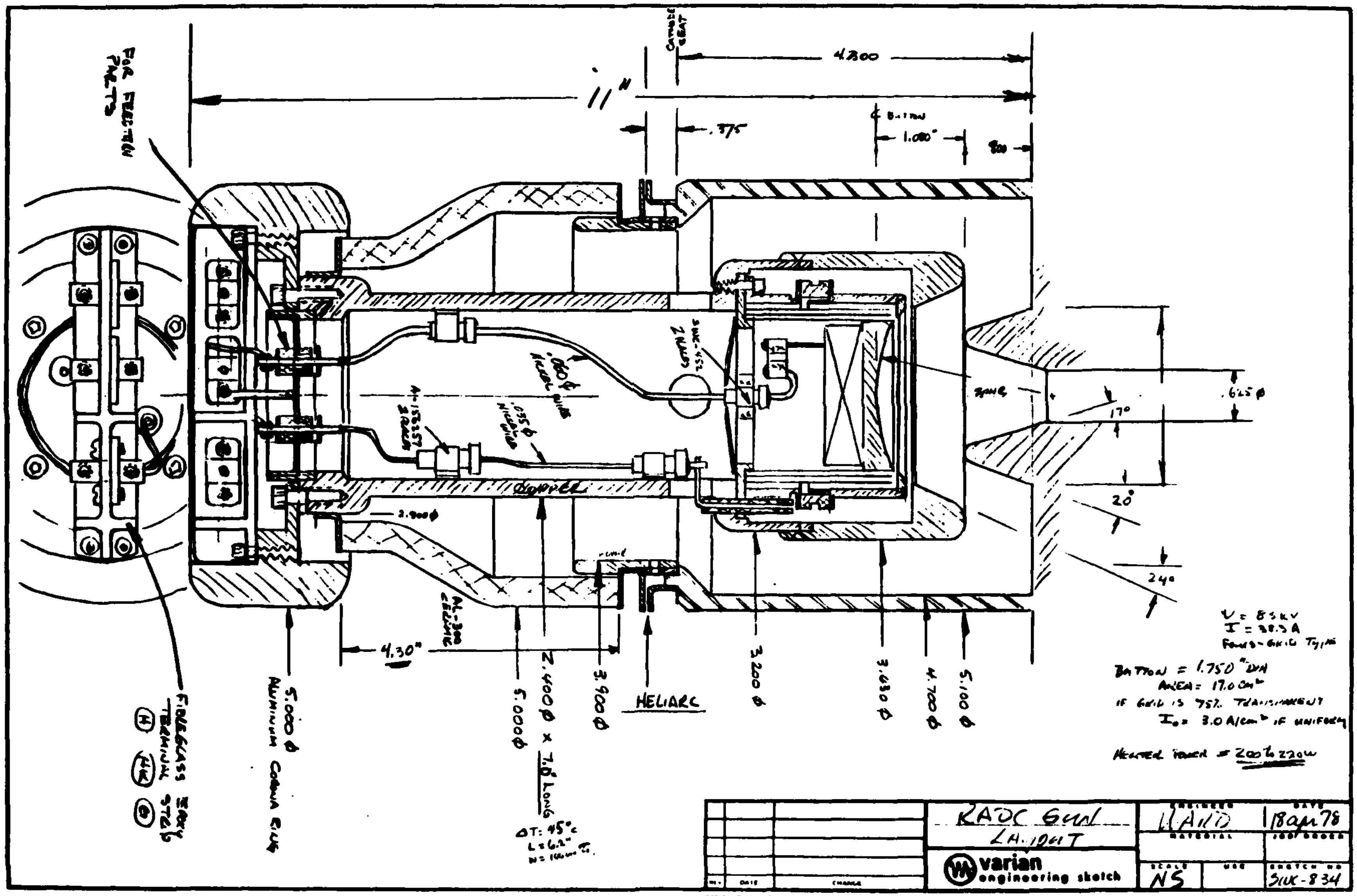

FIGURE 7. SKETCH OF TOTAL FULL-SCALE GUN ASSEMBLY

2. The total power input to the control grid, including both radiated heat from the cathode and intercepted beam power, was 12 watts distributed uniformly over the grid.

3. Grid cooling is almost entirely by conduction. (Grid temperature too low for appreciable radiation of heat.)

Under these conditions, the molybdenum control grid support ring will cperate at about 415°C, while the center of the grid will be near 750°C. Although the grid will function satisfactorily at these temperatures, a reduction in grid temperature can be achieved by increasing the thickness (not the width) of the grid webs.

During operation of the full-scale gun in the beam analyzer visual observations of the control grid were made and no thermal color could be seen; hence, the operating temperatures achieved were equal to, or less than, the calculated values.

VII. CONSTRUCTION OF FULL-SCALE GUN

Except for the grid set, no major problems were experienced in fabricating the parts for the full-scale gun. The grid set proved difficult to make because of the large size and the relatively deep dish cathode design. Small size radial vane grids are normally made by photo etching techniques. The procedure is to etch the grids from flat stock and then draw them to the desired curvature. While this method works well with smaller grids, the grids for the full-scale gun deformed unacceptably during the drawing operation.

The vendor making the grids ordered special equipment for making larger size photo etched grids, but the first experiments with the new equipment failed to produce acceptable grids. Time was not available to allow the vendor to perfect the improved grid making techniques; hence, an acceptable set of grids was made for the full-scale gun by electron discharge machining. In the EDM procedure, the grid blanks are drawn to shape and stressed relieved before the vanes are machined. This technique, although tedious, does produce acceptable large size grids.

Several months were required to assemble the full-scale gun. As is frequently the case with a new gun design, it was necessary to work out new jigs and tooling as the assembly proceeded. Figure 8 is a photograph of the full-scale gun.

FIGURE 8. FULL–SCALE GUN ASSEMBLY

VIII. FULL-SCALE GUN TEST RESULTS

The first attempt at testing the full-scale gun in the beam analyzer was terminated because relatively large amounts of grid emission made it impossible to obtain valid data. The grid emission problem was directly related to the large size of the full-scale gun.

The beam analyzer was designed for testing cathodes of less than 1 inch in diameter. The 0.511-inch diameter cathode used in the scale model gun is typical of the cathode size normally tested in the beam analyzer. The scale model gun required 30 watts of heater power for operation. In contrast, the full-scale gun, with its 1.8-inch diameter cathode, required a heater power of 225 watts, or seven and one-half times more power. Further, as described in Section VI, the full-scale gun was designed to operate in an oil or forced gas cooling environment, neither of which was available in the beam analyzer. Consequently, the grid structure in the full-scale gun operated at temperatures in excess of the design values and the result was a CW grid emission current on the order of a milliamp. While a grid emission of one milliamp might be acceptable at full operating voltages, in the beam analyzer where the average beam current measured is approximately 25 microamps, the one milliamp CW grid emission current totally swamped the test results and endangered the diagnostic target structure.

When it was determined that no useful data could be obtained without some form of external cooling, the full-scale gun was removed from the beam analyzer and fitted with a temporary cooling jacket. The gun was then returned to the beam analyzer and the cooling jacket was filled with a liquid dielectric. With the gun in a dielectric bath, the grid emission problem was eliminated and normal testing commenced.

The beam analyzer test results for the full-scale gun are shown in Figures 9, 10a, and 10b. Figure 9 shows the electrostatic (no magnetic focusing) beam profile data. The beam diameter at the beam minimum is approximately 480 mils. The beam cross sectional profile has the desired shape and shows no electron cross-overs.

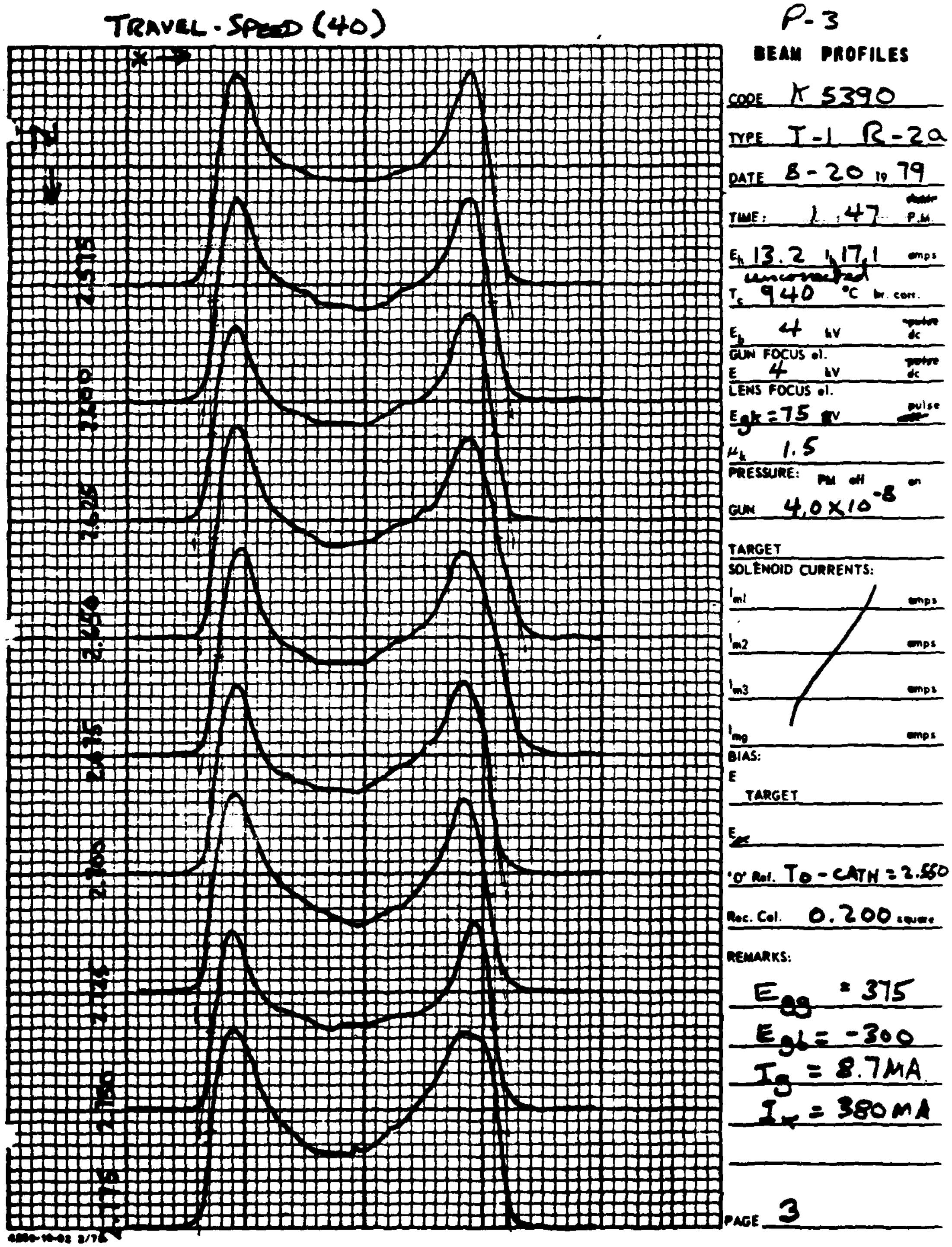

FIGURE 9. ELECTROSTATIC BEAM PROFILE DATA

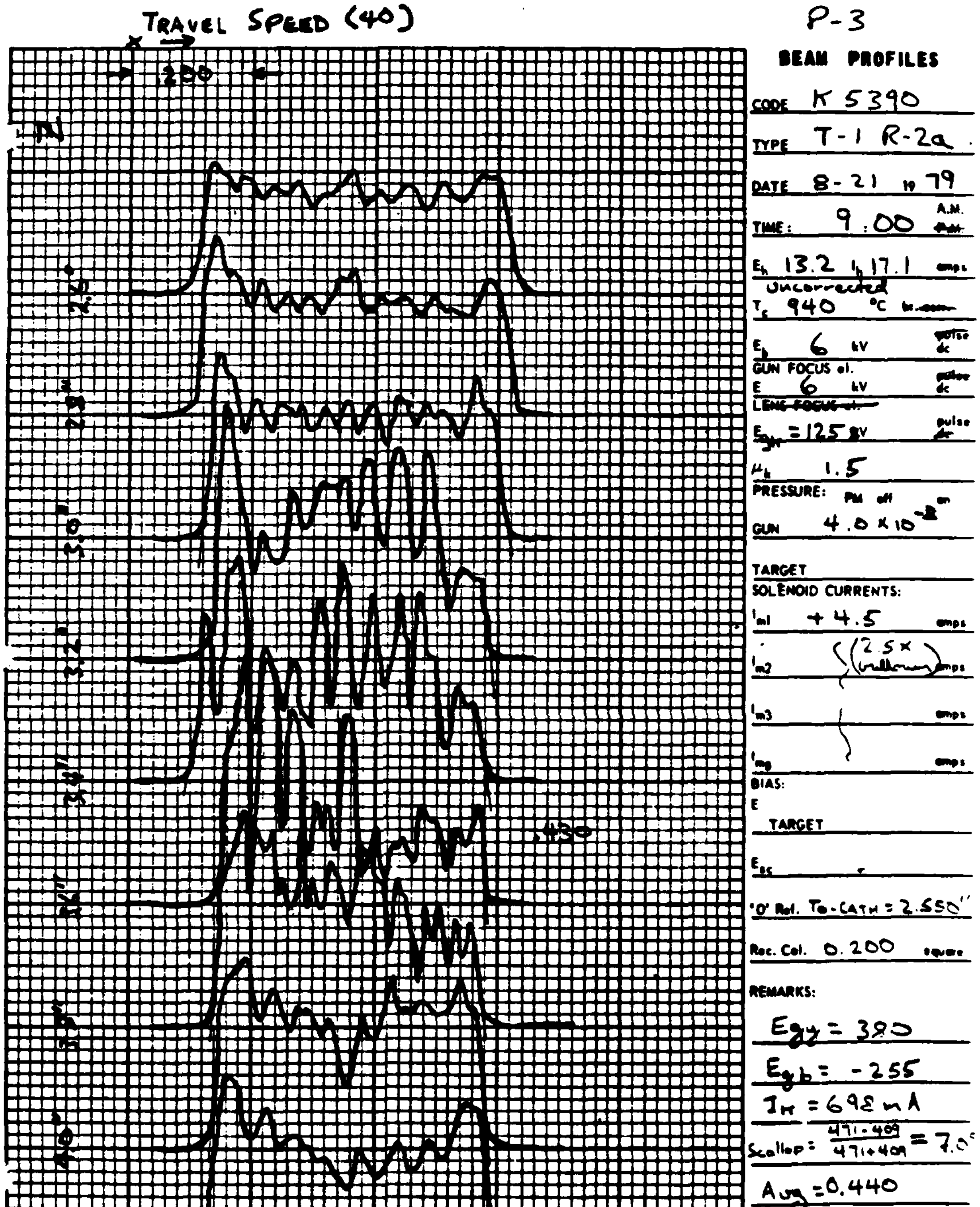

FIGURE 10a. BEAM PROFILE UNDER MAGNETICALLY FOCUSED CONDITIONS

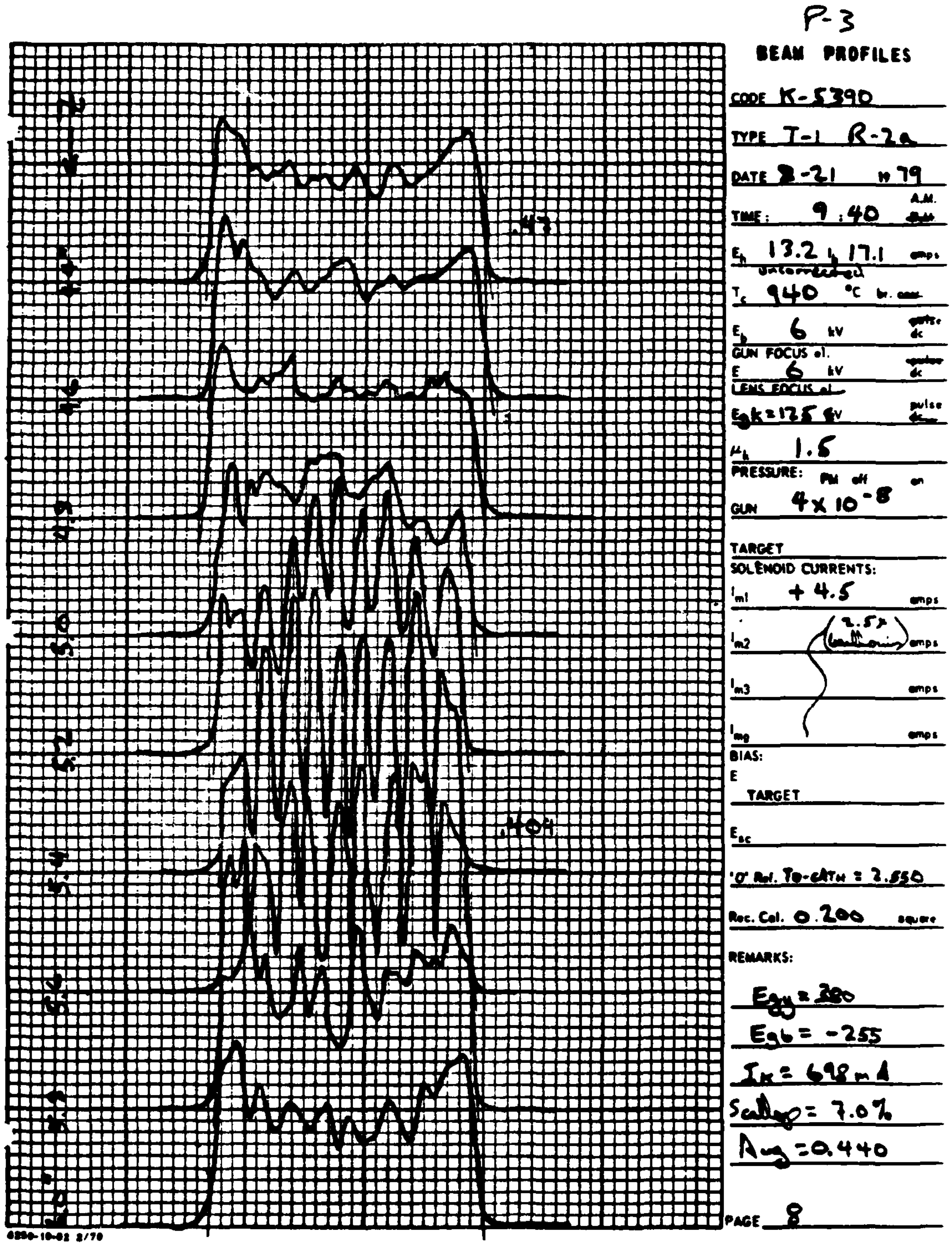

FIGURE 10b. BEAM PROFILE UNDER MAGNETICALLY FOCUSED CONDITIONS

Figures 10a and 10b show the beam under magnetically focused conditions. The proper focusing conditions for the full-scale gun were achieved by constructing a goal curve of the magnetic field shape in the cathode region from the paper design and the scale model test results. Iron polepieces which provide the desired field shapes were then determined experimentally. With these experimentally determined polepieces and a focusing field of approximately 2.5 times the Brillouin value, the results shown in Figures 10a and 10b were obtained.

Under focused conditions the beam scalloping was a very acceptable 7% and the average beam diameter was 0.440 inches. With this beam in the specified 0.625-inch diameter beam tunnel, the filling factor will be 70%.

The parametric performance of the full-scale gun is summarized in Table III. The first column gives the beam analyzer test data at 6 kV. The second column shows the beam analyzer data scaled to a beam voltage of 83 kV. The third column lists the specification maximum values.

At full voltage operation, the full-scale gun should meet all specifications with the exception of the heater power and the grid bias voltage required for cut-off. As expected, the heater power of 225 watts exceeds the specification value of 150 watts by a large amount. The grid bias voltage for cut-off of -70 volts at 6 kV scales to a -968 volts at 83 kV against a specification limit of -950 volts. In future versions of the full-scale gun, the -950 volt specification can be met by increasing the spacing between the cathode and the control grid by about 5 mils. This modification would also increase the grid turn-on voltage slightly which is in the desired direction for the final gun design.

The peak current intercepted by the control grid at 83 kV cannot be extrapolated from the 6 kV beam analyzer results because the intercepted grid current does not follow normal scaling laws as the beam voltage is increased. The current impinging on the control grid is made up of two components. One part comes from the fringes of each beamlet passing through the control grid; the rest is direct emission from the shadow grid.

Table III
Full-scale Gun Operating Characteristics

	Beam Analyzer Test Results	B.A. Results Scaled to 83 kV	SOW Specification Maximums
Beam Voltage (kV)	6	83	83
Beam Current (A)	0.698	38.3	38.3
Perveance ($I/V^{3/2}$)	1.6×10^{-6}	1.6×10^{-6}	1.6×10^{-6}
Heater Voltage (V)	13.2	13.2	13
Heater Current (A)	17.1	17.1	11.5
Heater Power (W)	225	225	150
Grid Voltage (V)	125	1850	3000
Grid Bias Voltage (V)	-70	-968	-950
Peak Control Grid Interception (MA)	8.7	<40	40

At 6 kV, thermal velocity effects are still large enough to cause an increase in the effective diameter of the beamlets leaving the cathode surface. As the beam voltage increases, the thermal velocity effects diminish. At 83 kV, the effective diameter of the beamlet leaving the cathode will be smaller and the percentage of intercepted beam current will be less.

The portion of the control grid interception coming directly from the shadow grid also does not scale proportionally to voltage. Since the surface of the shadow grid is covered with an emission inhibitor, emission from this element quickly becomes temperature limited as the beam voltage is increased. At the 6 kV beam voltage level in the beam analyzer, it is difficult to distinguish between the thermal velocity effects and the temperature limiting effects; hence, it is difficult to predict what the intercepted current will be at 83 kV. However, the intercepted grid current at 83 kV is expected to be less than 40 milliamps.

IX. SUMMARY AND CONCLUSION

A gridded gun, suitable for operating megawatt level linear beam tubes has been designed and tested at lower levels in a beam analyzer. The new gun features a shadow grid in contact with the cathode surface.

Extrapolations from the beam analyzer test data show that the gun should meet all performance objectives at full power except for heater power and grid bias voltage. The intercepted control grid current cannot be accurately estimated for full power operation, but it is believed that it will be less than the 40 milliamps specified.

The next step is to install the full-scale gun on an actual tube and evaluate performance.