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TECHNICAL REPORT ECOM-01666-5

HIGH-POWER HYBRID MULTIPLE-BEAM KLYSTRON FOR PHASED ARRAYS

FIFTH QUARTERLY PROGRESS REPORT

By

G. M. Branch—W. Neugebauer—H. L. Thal—J. R. M. Vaughan

MARCH 1967

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ARPA ORDER NO. 345, AMENDMENT NO. 2

CONTRACT DA 28-043-AMC-01666(E)
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15 SEPTEMBER 1966 TO 15 DECEMBER 1966

Report No. 5

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Prepared by
G. M. BRANCH — W. NEUGEBAUER — H. L. THAL — J. R. M. VAUGHAN
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For

U.S. ARMY ELECTRONICS COMMAND, Fort Monmouth, N. J.
Fort Monmouth, New Jersey

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ABSTRACT

Progress on the construction of the single-beam prototype was slowed but not stopped by a strike which continued throughout the greater part of the reporting period. Parts were accumulated from outside vendors, but almost no assembly was possible.

The gun design computer program was refined to include the effects of dimensional errors caused by thermal expansions or by tolerance build-up; these effects were investigated both theoretically and experimentally.

Based on the results of this investigation, a cathode mounting and jigging system has been devised which will allow any cathode of the 15-beam tube to be removed and replaced, with the necessary accuracy, without disturbing any other cathode.

The effect of unintended detuning of cavities (either by thermal effects or manufacturing tolerances) on the phasing in the output waveguide was investigated on the computer. It was found that this could be a serious problem -- at least one satisfactory single-beam tube design, which has been published, would be unusable as a unit of a multiple-beam tube for this reason -- but the specific design (No. 86) that we are using is found to be remarkably insensitive to minor detuning.

The basic design of the modulator for the 15-beam tube is described. A massive, simple, conventional line circuit discharged by three GL-7890 thyratrons will be used.

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RESULTS

A. GENERAL

Progress during the period September 15 to December 15, 1966 has been seriously curtailed, but not stopped, by a strike which began in mid-October and was still in progress at the end of the period. The strike has not prevented the engineering and supervisory staff from working in the plant, nor the placing of machine shop work outside. The timing is unfortunate, in that this period is one in which design work would have been at a minimum even without a strike, because the designs for the single-beam tube were essentially complete by September, and the detailed design of the 15-beam tube depends on the results to be obtained from the single beam tube. The engineering effort in this period would therefore have been primarily supervision of the parts-making and assembly, and the strike has simply made this slower and more difficult. However, the majority of the parts required for the single-beam tube were received from an outside vendor early in December, and the quality of workmanship on the difficult OFHC copper parts was excellent. The cavity parts, pole pieces, and collector parts are all in hand, and the input and output waveguides are close to completion.

Work has continued on the design of the 15-beam tube in areas not critically connected with the interaction. Since experience in earlier multiple-beam tubes showed that a break in the magnetic circuit on passing through the tube envelope produces surprisingly large and undesirable effects on the leakage field, it was decided to carry the magnetic circuit through the wall unbroken. Working out the details at the corners where the main box, the cathode box, the end plate supporting the input/output waveguides, and the magnet circuit all meet, and must be assembled in a logical order with welds between compatible materials in accessible places, took considerable time but is of no intrinsic interest. Work was also done on the method of mounting the cathodes to achieve the geometrical accuracy required (see Section C, Gun Alignment Accuracy), subject to the condition that it must be possible to replace any gun without disturbing any of the others, and maintain the same accuracy as in the original construction. This has been done, and the sketch designs will be converted into working drawings as soon as draftsmen are available again.

B. ELECTRON GUN DESIGN

During the last quarter, the digital electron gun program has been modified to include the effects of thermal electron velocities. An example of the result is given in Figure 1, which shows gun design No. 12 together with the beam profile within which 99 percent of the current will flow at 60 kilovolts. The beam voltage and cathode temperature must be specified as a computer input. This more accurate computation confirms the hand calculation shown in the last quarterly report and verifies that thermal velocities are negligible when this gun is operated at the design voltage of 60 kilovolts.

A beam tester is presently being constructed according to gun design No. 15, shown in Figure 2. The minimum beam diameter is 0.45 of the drift-tube diameter for electrons with no thermal velocities. At 60 kilovolts the minimum diameter of the 99-percent profile will therefore be 0.5 of the drift-tube diameter. The pole piece is shown in the optimum position as determined with the analog computer. Dimensions A and B have been adjusted to account for thermal expansion of the cathode mount.

Extensive tests have been made of the tungstate cathode and its mount to determine the dimensional changes due to temperature. The cathode was mounted in a metal bell jar having a flat glass window, and observations were made with a precision cathetometer capable of 0.001-inch resolution. The results of many measurements are given in Figure 3. The cathode is seen to be more dished, by 0.005 inch, at emitting temperature. This is an improvement over the 0.014-inch dishing of the oxide cathode reported previously. The cathode edge moved only 0.001 inch with respect to the focusing cup. The 0.014-inch expansion of the entire cathode mount is partially compensated by a 0.010-inch expansion of the large insulating ceramic.

The tungstate cathode required a new heater assembly. To determine whether or not the design is adequate for inclusion into a multiple-beam tube, the heater was subjected to a heat cycling test. After cycling at double power (150 watts) 100 times, with 5-minute-on and 5-minute-off periods, the filament still showed no signs of deterioration on the basis of a resistance measurement. Failure ultimately occurred when three times the normal input power was applied. The failure mechanism was a sagging of the filament, resulting in a short circuit between turns. On the basis of these measurements, it is felt that the new heater design is adequate for the multiple-beam tube.

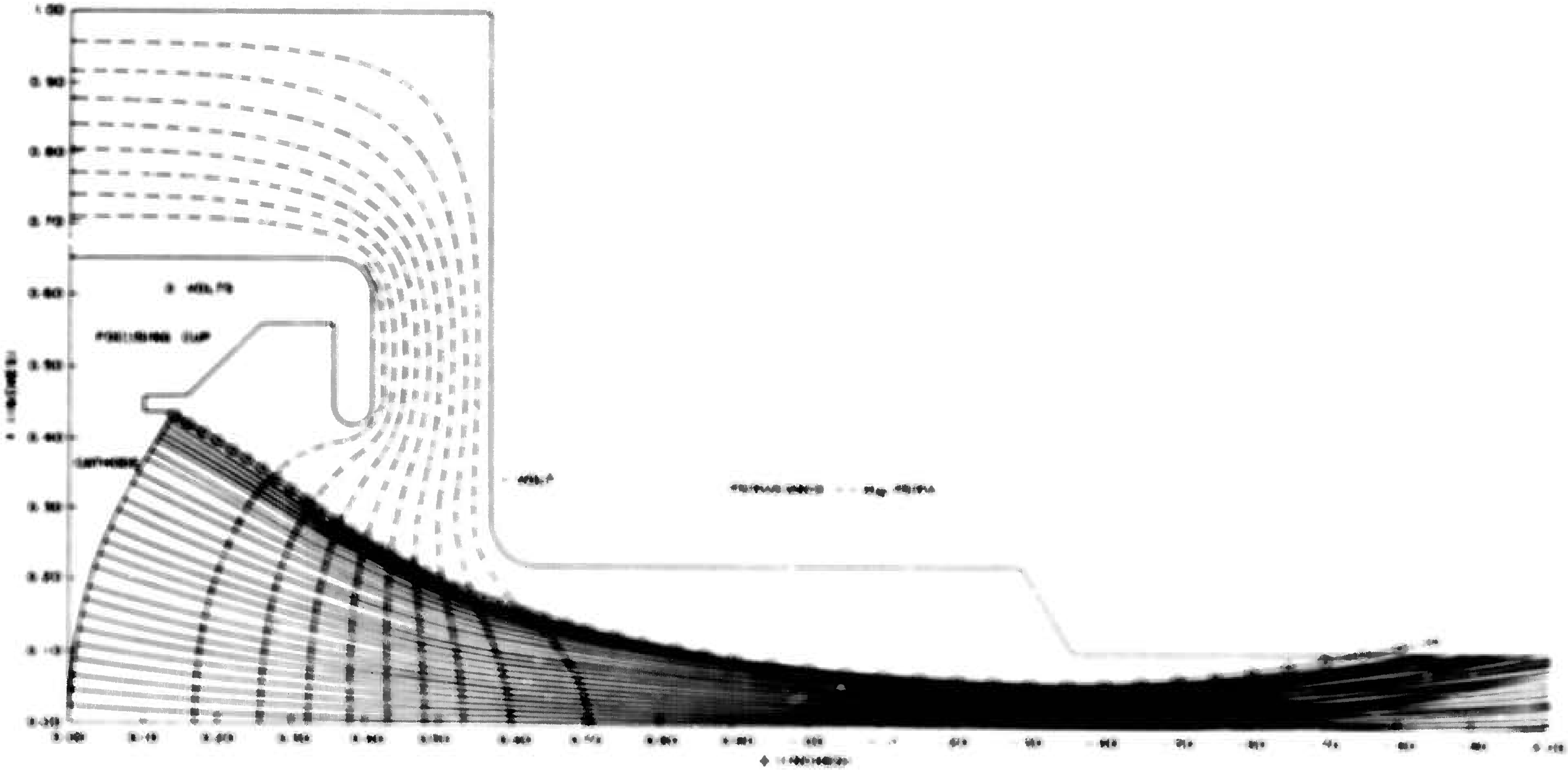

Figure 1 - Gun Design No. 17 (Circled Points Indicate the 95-Percent Boundary Allowing for Thermal Velocities)

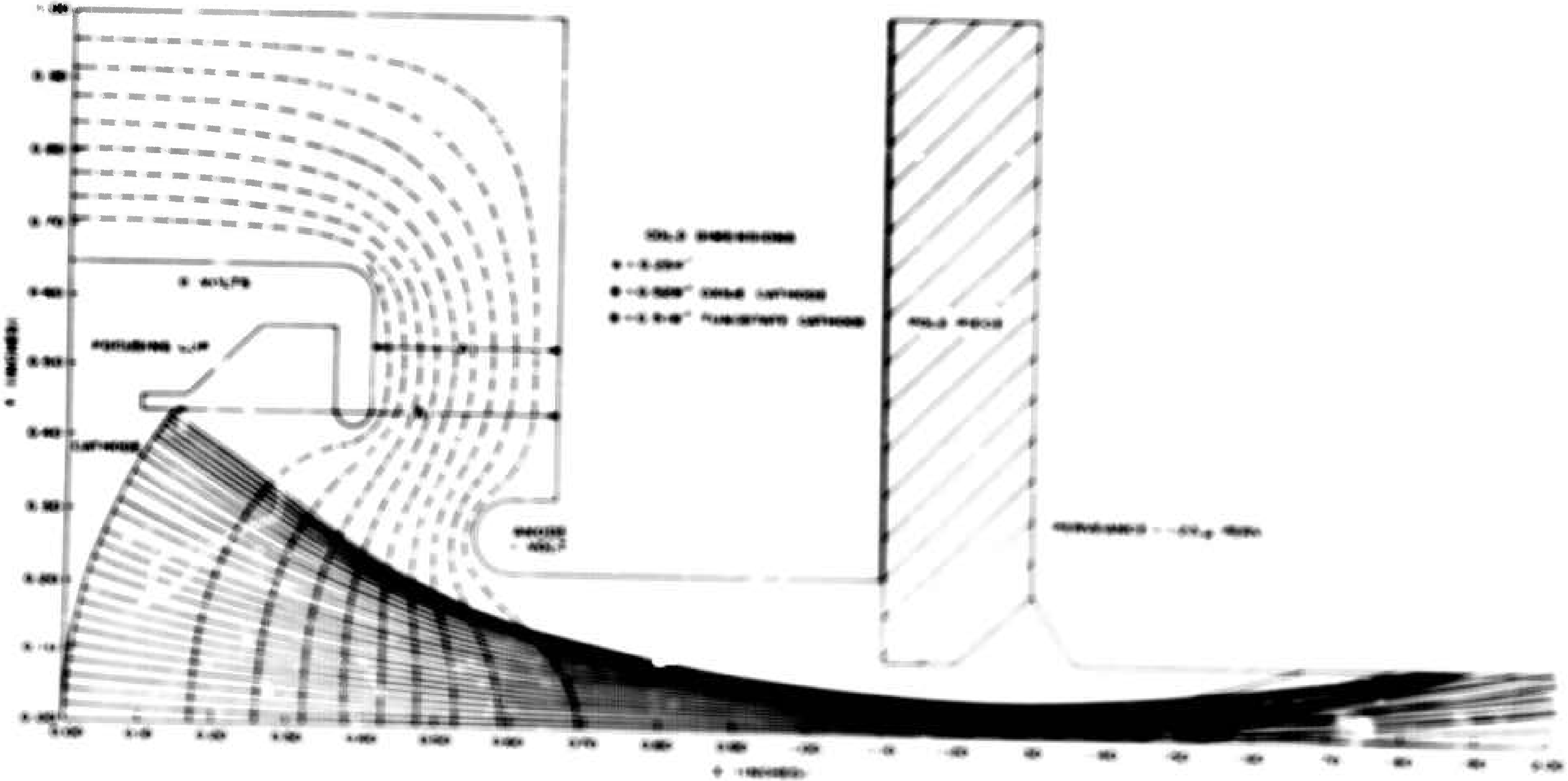

Figure 5 - Gun Design No. 17 (Sheet of Laminar Beam Contour)

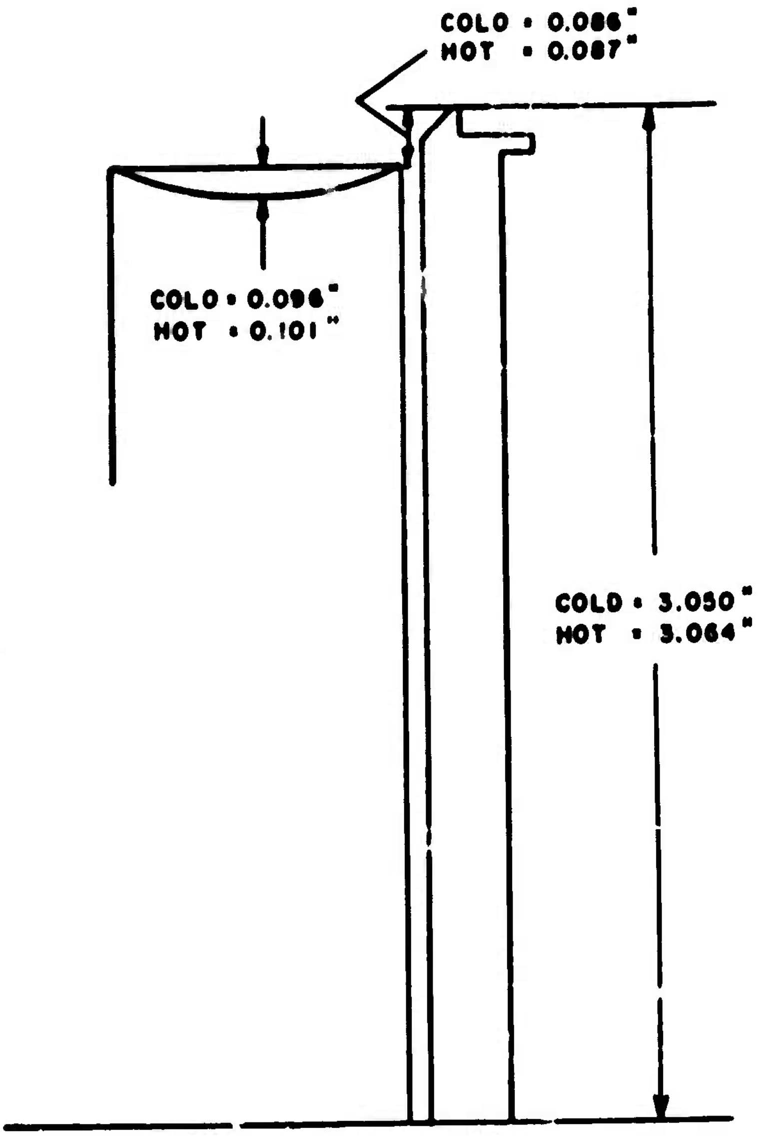

Figure 3 - Thermal Dimensional Changes for Tungstate Cathode

C. GUN ALIGNMENT ACCURACY

In order to determine the accuracy with which the gun spacing and centering must be maintained, a bell jar experiment was performed. A cathode assembly was mounted on a bellows device with calibrated micrometer movements in three directions; facing the cathode were an anode and water-cooled collector, insulated and separately metered.

The cathode was first centered with respect to the anode by minimizing the current intercepted on the anode. Then the axial spacing was varied. Figure 4 shows the perveance and interception as functions of the spacing; clearly, the minimum interception occurs at a spacing (0.208 inch) which gives considerably more than the design perveance of 1.3. The implication is that this cathode was too convergent, producing a beam waist at a point short of the tunnel entry. However, the cathode used in this experiment was not of the latest design; it was taken from an old beam tester, and the experiment is to be repeated with the final cathode design. Even though the absolute values of perveance are thus incorrect, the rate of change of perveance with spacing is probably quite accurate: if one accepts ±0.07 μperv as reasonable limits on perveance (corresponding to a ± 1-amp variation in the 19.1-amp design beam current), then Figure 4 indicates that the limits on gun spacing are ±0.014 inch. The measurements on thermal expansion changes in the cathode (reported in Section B, Electron Gun Design) show that the working position of the cathode is the result of the difference between a 0.014-inch expansion of the cathode assembly and a 0.010-inch expansion of the insulating ceramic. While this can be allowed for in setting the cathode spacing during assembly, it cannot be assumed that exactly the same expansions will occur under the different thermal conditions of the 15-beam tube. There will probably be ±0.005 inch uncertainty about the spacing in this tube, however accurately it is set initially. Thus, the available design tolerance is reduced to ±0.009 inch, and we must be able to determine what the correct value is within ±0.005 inch, and be able to set it (cold) within ±0.003 inch, in order to stay within tolerance.

Next, the sensitivity of interception on the anode, to transverse displacement (decentering) of the cathode, was measured. Figure 5 shows the results for two values of the spacing, one giving the nominal perveance and the other the optimum transmission when centered. It is evident from both curves that 0.010 inch of decentering produces a measurable increase in interception, so that a reasonable aim would be 0.003-inch accuracy of centering. Since the whole cathode structure is symmetrical, thermal expansion should not change this figure, but it is realistic to suppose that there will be some non-uniformity of heating, which will perhaps double this error.

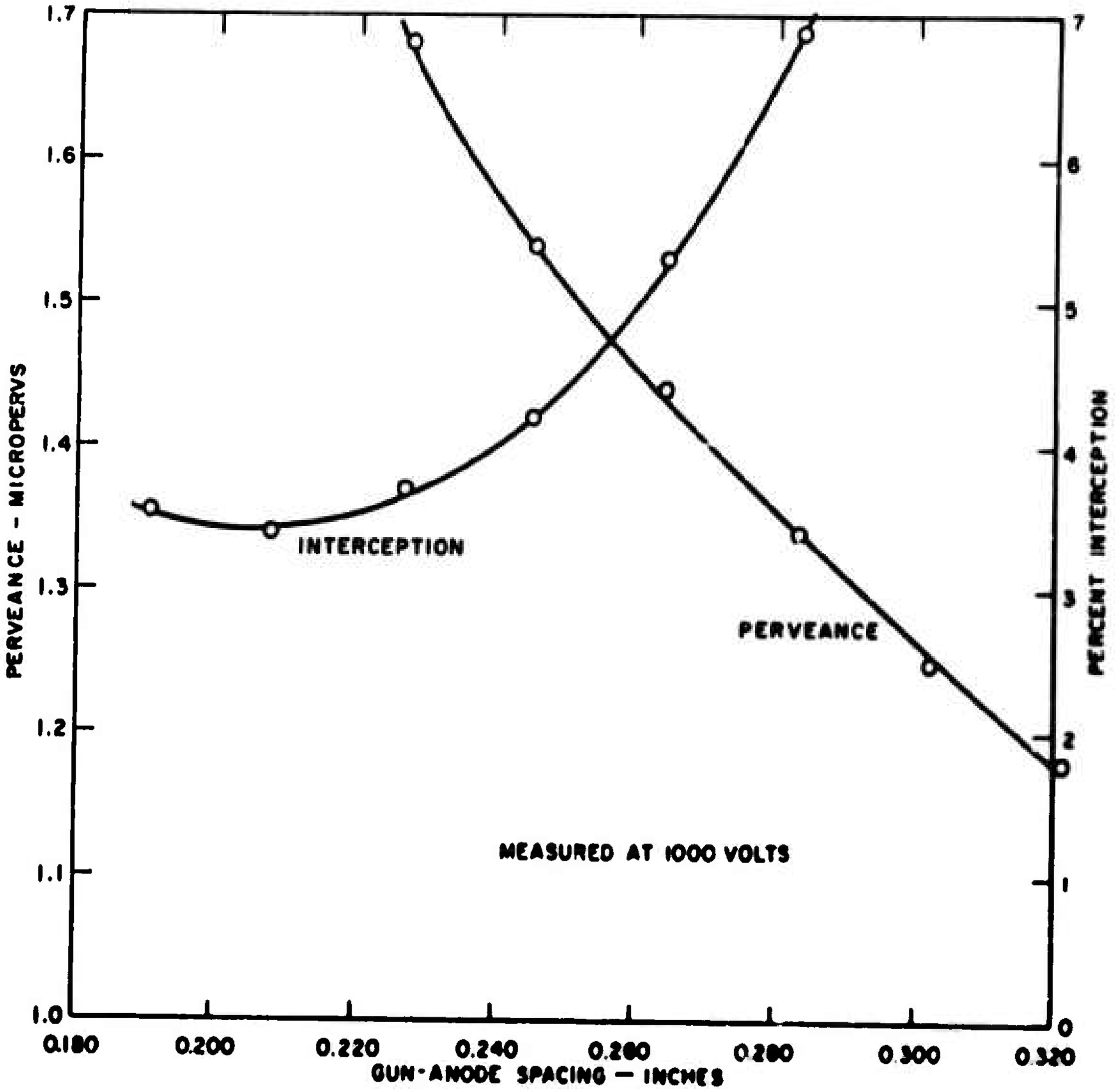

Figure 4 - Dependence of Beam on Gun Spacing

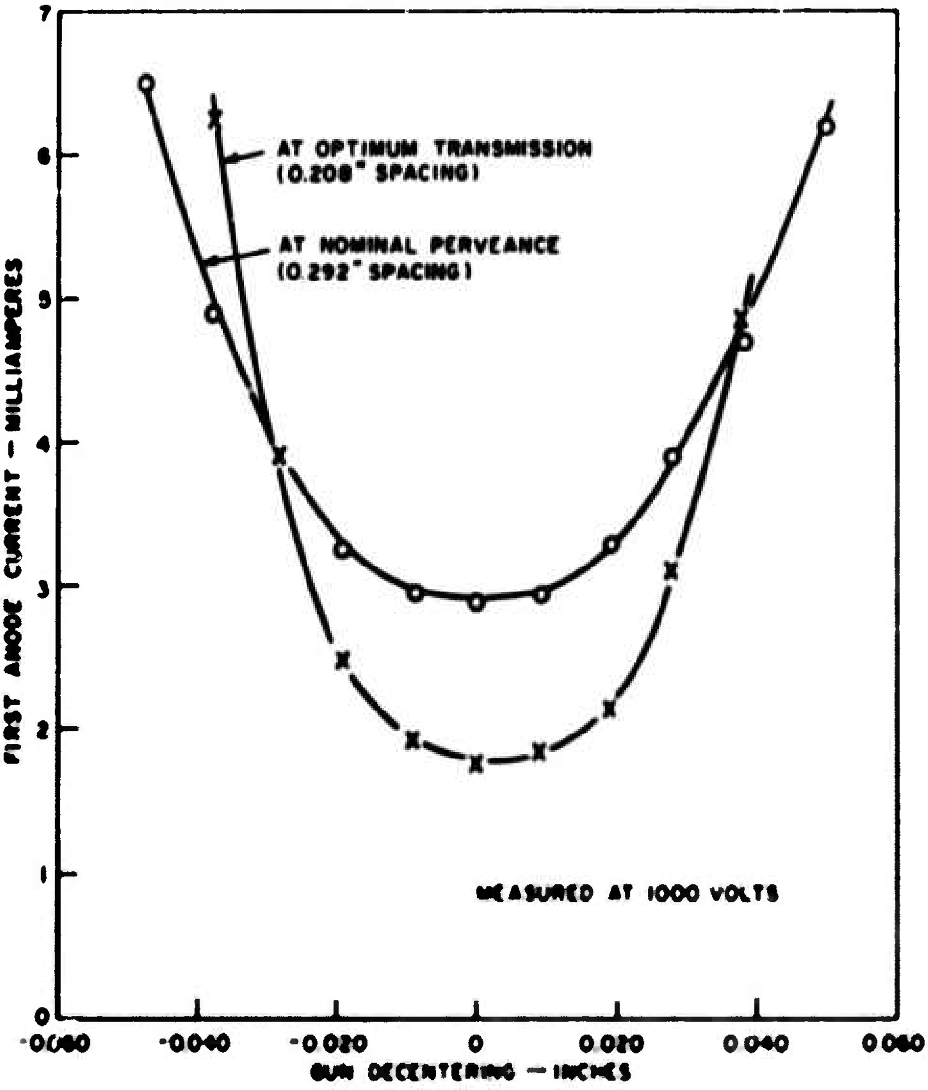

Figure 5 - Dependence of Beam on Gun Centering

The conclusion drawn from this experiment is that the cathode mounting system of the 15-beam tube must be such that the cathodes can be set in a desired position, relative to the anode, within 0.003 inch both radially and axially. The number of components which intervene between the anode and the working end of the cathode, is such that this tolerance could not be held simply by the geometry of the parts -- the individual part tolerances would be quite unreasonable.

Therefore, a jigging system has been designed which fits directly between the anode and the focus ring on the cathode, thus setting the accuracy with an absolute minimum of intervening parts; with the jigs in position, the final welds are made at the back end of the cathode structure, and the jigs can then be withdrawn axially through holes in the mounting plate. An advantage of this system is that if it is ever necessary to replace a cathode in the 15-beam tube, the replacement cathode can be centered and spaced to the same accuracy, without disturbing any other cathode.

D. PHASE SHIFT

Some concern was caused by reports on a British tube[1,2] which indicated phase shifts of considerable magnitude as a result of small (~0.1 percent) detuning of cavities. While unimportant in single-beam klystrons, shifts of the magnitude found by Dixon[1] would seriously upset the phasing in the output guide of a multiple-beam tube, causing a decrease in power output and an increase in the wasted power emitted from the reverse termination.

Data given by Kreuchen and Diserens[2] were sufficient to allow this tube to be simulated on the small signal program. This confirmed the general dependence on both penultimate tuning and drive level reported by Dixon, though the tuning dependence did not appear as severe as he found (about 8 degrees phase shift per MHz detuning of the penultimate cavity at S band, compared to Dixon's experimental figure of 20 degrees per MHz).

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[1] "Phase Relationships in a Stagger-Tuned Klystron Amplifier", N. E. Dixon. Proc. Inst. Electrical Engineers (British), 105, Part B Supplement No. 12, 1958.

[2] "Studies in the Development of High-Power Klystrons", K. H. Kreuchen and N. J. Diserens. Proc. Inst. Electrical Engineers (British), 105, Part B Supplement No. 12, 1958.

Dr. Branch's design No. 86 (reported in detail in Quarterly Report No. 3) was therefore checked for phase shift at the output gap, for ± 10 MHz detuning of each cavity in turn, and for drive level of 30, 100, and 300 watts.

The dependence on drive level was found to be less than 0.5 degree over the 30 to 300 watts range at 5400, 5650, and 5900 MHz. The dependence on cavity tuning was less than ± 1.05 degrees for ± 10 MHz detuning of any cavity, measured at 5650 MHz. The maximum effect was found at 5900 MHz, where a ± 10 MHz detuning of cavity No. 5 (pre-penultimate) results in a ± 3.7 degree phase shift. Since cos 3.7 degrees = 0.998, this is still a negligible effect as far as power summation is concerned. There is no question that the cavity frequencies can be preset to an accuracy better than ± 10 MHz without undue difficulty; the cavities received for the single-beam prototype are all within ± 3 MHz.

The conclusion of this investigation is that phase shift due to detuning or drive level can be a problem and needs to be investigated for any basic interaction design proposed for multiple-beam use; but design No. 86 proves to be extremely flat across the whole band for both effects, and no measurable degradation is expected.

E. ARPA C HYBRID MODULATOR

The design requirements for the ARPA C Hybrid modulator are:

65 KV peak at the tube
308 A peak (15 beams at approx. 20 A)
20 MW peak
4 μSEC pulse width
2500 PPS
0.01 duty
200 KW average

Choice of Circuit and Switch Tubes

Since the DC charging supply is an item of major cost for a high-power modulator, it is proposed that use be made of an existing supply capable of 750 KW (30 KV by 25 A). While the Blumlein voltage-doubling circuit appears to have advantages, it is not proposed here because high charging and switching currents and low network impedances are required. We plan to use a conventional modulator circuit consisting of three pulse-forming networks, charged in parallel by means of chokes and hold-off diodes and discharged in parallel by three GL-7890 hydrogen thyratrons. This tube type which was developed on Contract No. DA 36-039 SC-71230, has proven to be a rugged and reliable switch tube for such power levels. Taking into account the published tube ratings and the high duty, three tubes must be used to provide a conservative design. The remaining limitation is the commutation rate; this is approximately 3.5 KHz maximum for the GL-7890. To allow a reasonable margin of safety, a PRF of 2.5 KHz was chosen, the 0.01 duty requirement then fires the pulse length at 4 μSEC.

The block diagram of the modulator is shown in Figure 6; it is as simple as possible, but at this power level the components will be quite massive.

Pulse-Forming Networks

Each network will consist of ten sections to provide 4 μSEC of essentially flat pulse, with anticipated rise time of 0.2 μSEC and fall time of 0.5 μSEC.

Output Transformer and Shunt Load

A bifilar pulse output transformer will be required to step the peak voltage to 65 KV at the tube. A tapped primary provides the means for trimming the impedance match. It is planned to test the modulator alone by using an available 20-ohm water load of adjustable resistance and adequate power capability. To check the output transformer and to provide a shunt load for those cases where one or more beams may be made inoperative, another variable water load of 200 to, say, 600 ohms will be built.

Charging Choke

Resonant DC charging would be achieved with 0.16 henry. We plan a somewhat lesser value to assure full voltage-doubling during the charging cycle.

Charging and Clipper Diodes

Favorable reports from the General Electric Company's Heavy Military Electronic Equipment Department, Syracuse, indicate that semiconductor diodes are available to substitute for thermionic devices in the charging and clipping areas. Elimination of high-voltage-insulated filament supplies, blowers, and a possible Xray problem is expected. To provide a large safety factor, it is proposed that the diodes be used at half their rated inverse voltage. Eighty (80) GE Type 1N4510's are required in each string.

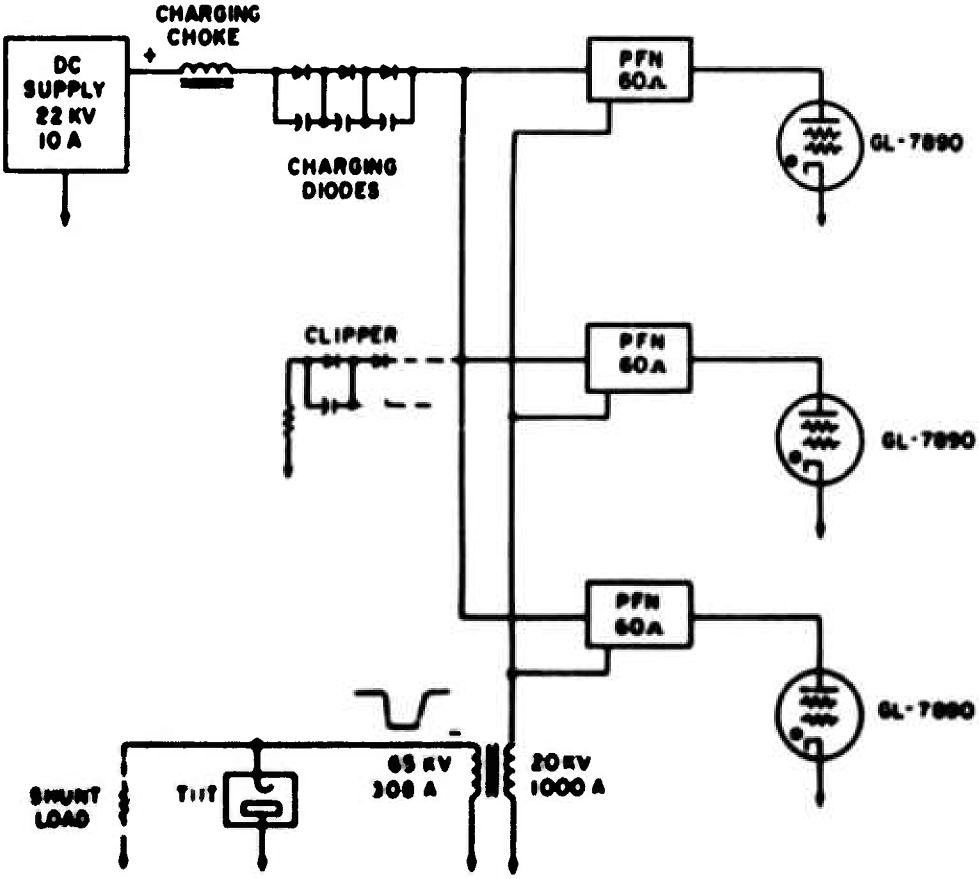

Figure 6 - Modulator Block Diagram

Driver for the 20-MW Modulator

A two-stage driver, Figure 7, is planned for triggering the modulator switch tubes. Again, semiconductor charging diodes will be used. A Hewlett-Packard pulse generator controls the pulse rate and synchronizes the instrumentation. Potted pulse networks of 2-μSEC duration are on order. No pulse transformers are required between stages, or between driver and modulator. It will be necessary, however, to construct the driver DC charging supplies and, possibly, a bias supply for the modulator switch tubes.

F. MODULATOR FOR 100-μSEC SINGLE-BEAM TESTS

Design requirements for single-beam testing at 100-μSEC are:

65 KV peak at the tube
20 A peak
1.3 MW
100 μSEC pulse width
Duty cycle as near to 0.01 as possible

An existing 40 KV modulator has been modified, Figure 8, to meet most of the requirements. A 100-μSEC line and a bifilar pulse transformer have been tested, and provide a full 65 KV at 3200 ohms. The duty, however, is limited to approximately 0.004, the maximum duty rating of the existing modulator itself. The full 0.01 duty will be achieved on the larger modulator for the 15-beam tube.

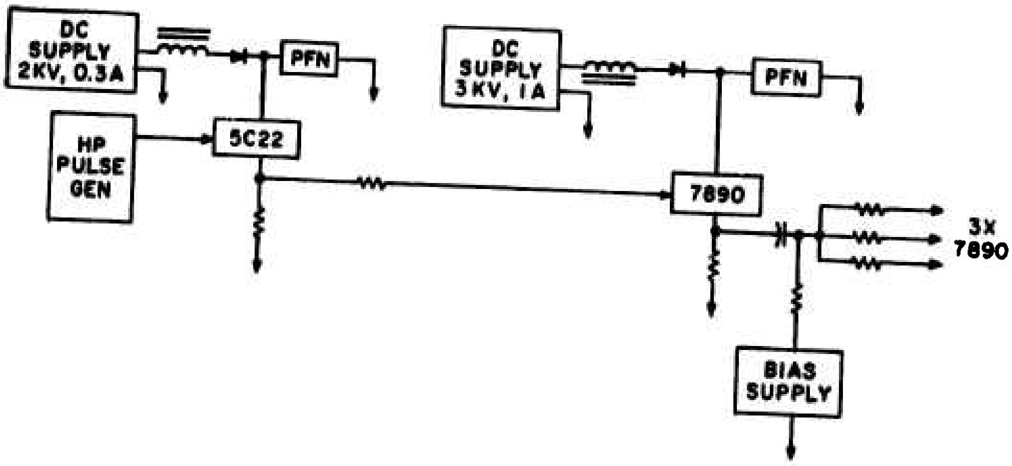

Figure 7 - Two-Stage Driver

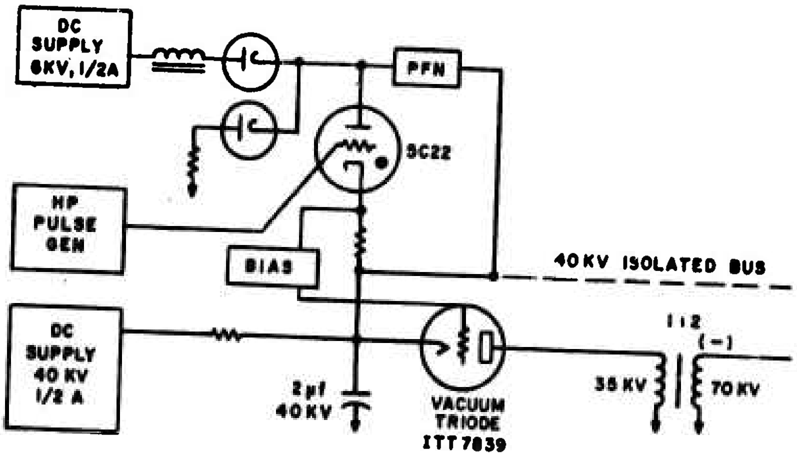

Figure 8 - 100-μSEC Hard-Tube Modulator

CONCLUSIONS

1. Further theoretical investigations have confirmed the apparent soundness of the design.

2. Enough parts are in hand to begin assembly of the single-beam tube as soon as workers are available (Note: the strike ended on January 9, 1967, and completion of the tube is now expected by February 25).

3. Design work has been carried out on the 15-beam tube, based on the theoretical beam and interaction studies.

RECOMMENDATIONS AND FUTURE PLANS

1. The most urgent task is completion and testing of the single-beam prototype, to check the design calculations.

2. Design work for the 15-beam tube should now be carried into the detail stage, leaving only a few critical dimensions open, pending results of the single-beam tests. It is not expected that these will affect the external dimensions in any way.

3. Construction of the 20-MW modulator should be started.

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(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1 ORIGINATING ACTIVITY *(Corporate author)*
General Electric Company
Schenectady, New York

2a REPORT SECURITY CLASSIFICATION
UNCLASSIFIED

2b GROUP
N/A

3 REPORT TITLE
HIGH-POWER HYBRID MULTIPLE-BEAM KLYSTRON FOR PHASED ARRAYS

4 DESCRIPTIVE NOTES *(Type of report and inclusive dates)*
Fifth Quarterly Progress Report - 15 September 1966 to 15 December 1966

5 AUTHOR(S) *(Last name, first name, initial)*
Branch, G. M. - Neugebauer, W. - Thal, H. L. - Vaughan, J. R. M.

6 REPORT DATE
March 1967

7a TOTAL NO OF PAGES
16

7b NO OF REFS

8a CONTRACT OR GRANT NO.
DA 28-043 AMC-01666(E)

b. PROJECT NO.
7900.21.223.12.00.50.410-5

c

d

9a ORIGINATOR'S REPORT NUMBER(S)

9b OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*
ECOM-01666-5

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ARPA
ARPA ORDER NO. 345
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12 SPONSORING MILITARY ACTIVITY
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DD FORM 1 JAN 64 1473

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