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DESIGN OF A MULTISTAGE DEPRESSED COLLECTOR FOR THE F-16 RADAR DUAL MODE TRANSMITTER TUBE

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BACKGROUND INFORMATION

This is a formal presentation of the proposed design of a multistage depressed collector (MDC) for use with the F-16 Radar Dual Mode Transmitter Tube being built by Hughes Aircraft Electron Dynamics Division (HEDD). This work was undertaken in response to a request on November 10, 1981 by Colonel Stuart T. Boyd, USAF, Director of Projects, Deputy for F-16. In addition to the design itself, some of the rationale and methodology employed are also presented here. Copies of most of the drawings, graphs, and tables presented here were made available to HEDD as soon as they were completed.

Over the past eight years several Traveling Wave Tubes (TWT's) equipped with MDC's and operated under a variety of conditions have been studied analytically and experimentally at Lewis Research Center as a part of a joint USAF-NASA program to improve the efficiency of TWT's used in communication and electronic counter measure systems. The results of this work, which have been described in numerous publications (refs. 1 to 6), have shown that the computational methods employed are sufficiently accurate and reliable to be used in the design and analysis of TWT's with helical slow wave circuits.

Much of this success is due to the multidimensional helical TWT computer program, developed at Lewis Research Center, that produces a reliable mathematical model of the spent electron beam. Unfortunately, a comparable computer program does not exist for coupled cavity tubes such as the F-16 Radar Tube. Although an effort is underway at Lewis Research Center to develop a coupled cavity TWT computer program, the results of this work will not be available for several months at least and can have no impact on the design described here. The spent electron beam model used in these calculations is described in detail in the next section.

As a further caveat it should be pointed out that no computer program can do more than analyze a mathematical model of a general tube type. Any particular tube of that type might have characteristics somewhat different from the model. When the inaccuracies inherent in modeling so complex a problem are added to the above considerations the design described here should be expected to undergo some empirical iterations before it is optimized.

SPENT BEAM MODEL

The first step in the design or analysis of an MDC is to produce a mathematical model of the spent electron beam exiting the TWT. In this case, three sets of data for the spent beam kinetic energy distribution were made available by HEDD, a measured distribution, a three-dimensional computed distribution, and a one-dimensional computed distribution. The two computed distributions

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were outputs of a coupled cavity TWT program originally due to J. R. M. Vaughan of Litton.

Because the performance of an MDC is dependent on the angular and radial distributions as well as the energy distribution of electrons in the spent beam, the preferred choice for use in the design was the three-dimensional computed distribution. It was quickly discovered, however, that the energy balance for these data were substantially in error, and they were used primarily as a guideline to form a crude angular distribution for the high mode.

The energy distribution for the spent beam mathematical model that was used in this design was derived from the one-dimensional computed distribution, adjusted slightly to achieve an approximate energy balance. The beam was divided into 24 energy classes with equal current. The distribution for the low mode is shown in figure 1, plotted on the energy distribution measured by HEDD. For the high mode, this information is plotted in figure 2. It is encouraging that the computed one-dimensional distributions are in reasonable agreement with the measured distributions.

The measured intercepted current in the low mode can be seen in figure 1 to be about 4 percent and in the high mode from figure 2 to be 28 percent. The computed values of intercepted current were zero in the low mode and 4 percent in the high mode. Presuming that the measured intercepted current will be substantially reduced as the tube is developed, no attempt has been made to resolve this discrepancy. The total current in the model of the spent beam used in these calculations was 0.65 A in the low mode and 3.59 A in the high mode. As presented in figures 1 and 2, the computed distributions have been scaled so that they can be directly compared to the measured spent beam current distributions.

The large diameter and length available for this collector, relative to the beam diameter, reduced the dependence of the collector performance on the radial distribution of electrons in the spent beam. Because of this and because no reliable radial distribution was available anyway, the centroid of charge for all rays in the mathematical spent beam model was arbitrarily set at 0.75 mm for the low mode and 1.5 mm for the high mode. These beam radii are at least as large as most of the radii listed in the three-dimensional computed distribution.

The angular distribution used for the low mode was obtained by equally dividing the current for each energy class into rays of charge launched at angles with respect to the tube axis of 0^o, $+3^o$, and -3^o, making a spent beam model of 72 rays. For TWT's with relatively low electronic efficiency and perveance as in the low mode, $\pm 3^o$ is a reasonable estimate that should define an envelope containing most of the electrons. To determine the sensitivity of the collector to the angular distribution, the computation was repeated for the low mode for a beam with angles of 0^o, $+6^o$, and -6^o with the result that the computed collector efficiency was approximately one percentage point lower than that for the 3^o beam.

The angular distribution for the high mode spent beam mathematical model could not be done so simply. Because of the larger beam diameter and larger space charge forces, the collector is more sensitive to the angular distribution in the high mode than in the low mode. Also, because the high mode is operated at or near saturation, the disorder in the beam, including the angular distribution, will be greater. Without changing our version of the Herrmannsfeldt program (ref. 7) it was not possible to compute the high mode collector current distribution with sufficient variation in the angular distribution in one computer run. What was done was to make three computations with the same total beam current in each. For the first computation the current was divided equally into 72 rays with a ray of 0^{o}, $+3^{o}$, and -3^{o} for each of the 24 energy classes as was done for the low mode. The other two computations were each of 48 rays, one with $+6^{o}$ and -6^{o}, the other $+9^{o}$ and -9^{o} for each of the energy classes. The space charge forces near the entrance to the collector, where most dispersion due to space charge will occur, were approximately the same for each computation. The current and energy dissipation for the pole piece and each of the collector electrodes were then calculated using a weighting formula derived from the three-dimensional computed distribution, which indicated that 63.4 percent of the spent beam had angles between +3 and -3^{o}, 23.7 percent between 3^{o} and 6^{o}, and 12.9 percent of greater than 6^{o}. Therefore, the current to each collector and the pole piece was computed by summing 63.4 percent of the current from the 0-3^{o} distribution, 23.7 percent of the current of the 6^{o} distribution, and 12.9 percent of the 9^{o} distribution. The energy dissipation was computed similarly.

The validity of the above approximation made for the high mode has since been established by redoing the three part computation for the final design as one computation using a newly revised version of the Herrmannsfeldt program.

DESIGN METHODOLOGY

As originally outlined, the problem was to design an MDC with as high an efficiency in the low mode as possible. It soon became apparent, however, that to literally follow that direction would lead to a design in which the high mode dissipation on the pole piece and the first depressed stage would be excessive. The design presented here represents a compromise of a few percentage points in low mode collector efficiency while maintaining the average rates of dissipation on the depressed collector electrodes for the high mode at levels less than or only slightly higher than those for the low mode. This was achieved by operating the first collector stage at a less depressed potential than was optimum for the low mode while tailoring the collector geometry to prevent backstreaming to the tube body by negative angle, lower energy class electrons.

As the collector was originally conceived, the material of choice for the electrode materials was pyrolytic graphite because of its superior thermal conductivity and low secondary electron yield (refs. 8 and 9). The original collector design incorporated an array of flat plates that might be fabricated from a single large plate of pyrolytic graphite at relatively low cost in a production tube. However, because the brazing, outgassing, and high voltage performance of pyrolytic graphite are still the subject of experimental investigations, collector efficiency calculations were performed assuming secondary yields of 0.4 (sputtered pyrolytic graphite), 0.6 (sputtered titanium carbide), and 1.0 (copper).

According to HEDD measurements, magnetic fields within the collector are negligible. As much as possible, collector dimensions were tailored to accommodate HEDD fabrication techniques and to make use of the same insulators and cooling fins as the HEDD designed collector as presented in the drawings supplied.

COLLECTOR DESIGNS

The first design of a flat plate collector was transmitted to HEDD on December 18, 1981. The design is shown in figure 3 in which the collector dimensions in centimeters have been added to the computer-generated drawing of the low mode $\pm 3^{\circ}$ beam trajectory plot. The computer-generated drawings of the collector trajectories present a cross-sectional view of the collector. The bottom line of the drawing is the center line of the collector. The edges of the pole piece and the collectors are shaded. Equipotential lines are labeled with their voltage, expressed as a fraction of the tube voltage. The trajectories for the high mode are shown in figures 4, 5, and 6.

A summary of the collector efficiency, current distribution, and dissipated power for this collector for a variety of cases is presented in table 1. The low mode collector efficiency can be seen to be just under 90 percent and the average high mode pole piece dissipation is 225 W when the first depressed stage is fabricated from sputtered pyrolytic graphite. An examination of figures 4, 5, and 6 will show that there is considerable electron bombardment of the aperture of the first depressed stage during high mode operation. The average heat flux to the first stage aperture can be calculated to be 76.9 W in the high mode. Aside from delivering a potentially damaging heat load to the first collector, this electron bombardment results in a large current of secondary electrons streaming to the pole piece. This effect becomes particularly pronounced if higher secondary yield materials are used to fabricate the collector electrode as can be seen in table 1.

These potential thermal problems were avoided by a redesign of the MDC that greatly reduces the electron bombardment of the first stage aperture in the high mode. The new dimensions and the low mode trajectories are shown in figure 7. The high mode results are presented in figures 8, 9, and 10. A summary of the computations for this modified flat plate collector is presented in table 2. This design, which was mailed to HEDD on January 6, 1982 reduces the average heat flux to the first depressed collector aperture to 5.8 W in the high mode. Furthermore, the dissipation on the pole piece is very substantially reduced and much less sensitive to secondary electron yield. This redesign does very slightly reduce collector efficiency in the low mode, but would appear to be perferable to the original, flat plate design. The collector efficiency in the high mode is increased substantially.

Both collectors employ a flat back plate to permit high energy electrons to ride as far into the structure as possible, increasing the probability that secondary electrons emitted form the back wall will travel no further than the next depressed stage. The spike at the center of the back wall is quite pointed, the better to deflect high energy, negative angle electrons. No attempt was made to incorporate magnetic refocusing in the design. Mechanical details such as the size and locations of cooling fins and the placement of optical baffles to block electrons from bombarding insulating materials were not included in the design at this point. To a certain extent these details must be supplied by the engineers at HEDD who will have responsibility for the tube fabrication and packaging.

On February 17, 1982 a drawing of the mechanical layout of the collector was received from HEDD. The layout made some modifications to the January 6 MDC design in order to provide optical baffles to shield the insulators and to make use of the same insulators and cooling fins as the HEDD designed collector. The pole piece aperture and thickness were also changed at this time. This mechanical layout was studied and several changes were suggested as shown in figure 11. The changes were proposed in order to maintain the collector efficiency at the level predicted previously, to reduce the liklihood of high voltage breakdown between stages, to improve the shielding of the insulators from electrical bombardment, and to improve the thermal conductivity of the structure. The layout was marked to show the dimensions of the proposed changes and to indicate where coatings should be applied to suppress secondary electron emission. The drawing as shown in figure 11 was returned to HEDD on March 5, 1982.

A computer drawing of the trajectories of this revised MDC design for the low mode 3^{o} case is shown in figure 12 with the dimensions added in centimeters. The high mode cases for this design are shown in figures 13, 14, and 15. A summary of the MDC efficiencies, collector currents, and average collector dissipations for this design are presented in table 3. The change in geometry required a slight decrease in the depression of the third stage in order to approximately maintain the same MDC efficiencies as in table 2. The current and dissipation on collector 3 increased primarily at the expense of collector 2. Other changes between table 2 and table 3 are not very great. The information in tables 2 and 3 and figure 12 were mailed to HEDD on March 12, 1982.

CORRECTED HIGH MODE CALCULATION

Subsequent to the delivery of the revised MDC design to HEDD, the version of the Herrmannsfeldt program in use at Lewis Research Center was revised to accommodate a number of larger computational parameters. The calculation of the high mode case for the configuration of March 5, which had required three separate computer runs, was redone in a single computer run, making use of the expanded capability of the revised program. The computer drawing of the trajectories for this case is shown in figure 16. A summary of the current distribution and average power dissipation is presented in the first three cases shown in table 4. For the convenience of comparison, the last three cases of table 3 are repeated at the end of table 4. For the single computation of the high mode there is a moderate increase in the current and power dissipation at the pole piece which results in a slight degradation of collector efficiency.

The power dissipation at the aperture of the fist depressed stage has also been recomputed as 18.6 W. Using the three computation approximation it has been previously reported to be only 5.8W.

The corrected high mode calculation also indicates that there is sufficient dispersion due to space charge in the collector to deflect high energy elections and prevent direct bombardment of the spike. The pointed spike, as previously specified, is not necessary, and in fact is a possible source of arcing during operation. It is recommended that the spike end be more or less spherical in shape as has been the case in earlier designs we have published.

None of the other high mode results was recomputed.

RECOMMENDATIONS

It is recommended that HEDD build a collector using the second design sent to them on January 6, 1982 and revised on March 5, 1982.

In order quickly to obtain data for use in a possible redesign of the collector, it is recommended that the first collector be made of copper, possibly with soot or sputtered titanium carbide used to suppress secondary emission. Eventually the best MDC performance can be expected to be obtained with collector plates of sputtered pyrolytic graphite.

It would appear from the analytical results presented here and from other information supplied by HEDD that the HEDD TWT may have a spent beam energy distribution sufficiently different from that of the TWT supplied for the same system by Litton that it would achieve an optimum MDC performance with somewhat different collector voltages and currents. This remains to be verified experimentally, since it has been our experience that the collector current distribution is difficult to predict accurately.

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NAS 1.15:82982 82/11/00 18 PAGES UNCLASSIFIED DOCUMENT
UTTL: Design of a multistage depressed collector for the F-16 radar dual mode transmitter tube
AUTH: A/DAYTON, J. A., JR.
CORP: National Aeronautics and Space Administration. Lewis Research Center, Cleveland, Ohio. AVAIL.NTIS SAP: HC A02/MF A01
MAJS: /*COMPUTER PROGRAMS/*ELECTRON BEAMS/*ENERGY DISTRIBUTION/*KINETIC ENERGY/* RADAR TRANSMISSION/*TRAVELING WAVE TUBES
MINS: / DESIGN ANALYSIS/ ELECTRONIC COUNTERMEASURES/ HELICAL ANTENNAS/ MATHEMATICAL MODELS/ RADAR EQUIPMENT/ WAVE PROPAGATION
ABA: E.A.K.

TABLE 1

CURRENT & AVERAGE DISSIPATION FOR FLAT PLATE COLLECTOR

	EFFICIENCY	POLE PIECE 0V[1]	ELECTRODE 1 -13875V	ELECTRODE 2 -18875V	ELECTRODE 3 -22175V	ELECTRODE 4 -24875V
LOW MODE 3^{o} BEAM δ = 0.4	89.9%	NONE	162.5 mA	193.2 mA	245.6 mA	48.8 mA
			213 W	170 W	172 W	82 W
δ = 0.6	89.5%	NONE	162.5 mA	195 mA	260 mA	32.5 mA
			213 W	173 W	192 W	82 W
δ = 1.0	88.8%	NONE	162.5 mA	198.6 mA	288.9 mA	0 mA
			213 W	179 W	232 W	82 W
LOW MODE 6^{o} BEAM δ = 0.4	89.0%	NONE	162.5 mA	225.7 mA	218.5 mA	43.3 mA
			213 W	220 W	183 W	76 W
HIGH MODE						
δ = 0.4	71.4%	.537 A	1.773 A	.668 A	.505 A	.108 A
		225 W	228 W	66 W	73 W	22 W
δ = 0.6	67.8%	.680 A	1.693 A	.651 A	.494 A	.073 A
		285 W	238 W	70 W	76 W	22 W
δ = 1.0	60.6%	.968 A	1.532 A	.615 A	.473 A	0 A
		405 W	257 W	79 W	82 W	22 W

1 VOLTAGES REFERENCED TO GROUND

TABLE 2

CURRENT & AVERAGE DISSIPATION FOR MODIFIED COLLECTOR

	COLLECTOR EFFICIENCY	POLE PIECE 0V[1]	ELECTRODE 1 -13875V	ELECTRODE 2 -18875V	ELECTRODE 3 -22175V	ELECTRODE 4 -24875V
LOW MODE 3° BEAM δ = 0.4	89.7%	NONE	162.5mA	198.6mA	240.1mA	48.8mA
			214 W	181 W	173 W	83 W
δ = 0.6	89.4%	NONE	162.5mA	198.6mA	256.4mA	32.5mA
			214 W	181 W	193 W	83 W
δ = 1.0	88.7%	NONE	162.5mA	198.6mA	288.9mA	0mA
			214 W	181 W	232 W	83 W
LOW MODE 6° BEAM δ = 0.4	88.9%	NONE	162.5mA	225.7mA	218.5mA	43.3mA
			214 W	221 W	184 W	77 W
HIGH MODE δ = 0.4	76.9%	.264A	2.005A	.706A	.496A	.118A
		109 W	212 W	84 W	63 W	28 W
δ = 0.6	75.4%	.296A	2.061A	.655A	.499A	.079A
		122 W	225 W	88 W	66 W	28 W
δ = 1.0	72.3%	.361A	2.171A	.553A	.505A	0A
		149 W	251 W	95 W	73 W	28 W

1 VOLTAGES REFERENCED TO GROUND

TABLE 3

CURRENT & AVERAGE DISSIPATION FOR COLLECTOR DESIGN 3. 5, 82

	COLLECTOR EFFICIENCY	POLE PIECE 0V[1]	ELECTRODE 1 -13875 V	ELECTRODE 2 -18875 V	ELECTRODE 3 -21975 V	ELECTRODE 4 -24875 V
LOW MODE			162.5mA	166.1mA	272.6mA	48.8mA
3^{0} BEAM	89.5%	NONE				
δ = 0.4			224 W	144 W	212 W	88 W
			162.5mA	167.9mA	287.1mA	32.5mA
δ = 0.6	89.1%	NONE				
			224 W	146 W	233 W	88 W
			162.5mA	171.5mA	316.0mA	0mA
δ = 1.0	88.3%	NONE				
			224 W	151 W	276 W	88 W
LOW MODE			162.5mA	184.2mA	265.4mA	37.9mA
6^{0} BEAM	88.8%	NONE				
δ = 0.4			224 W	170 W	241 W	71 W
HIGH MODE		.288A	2.055A	.635A	.485A	.127A
δ = 0.4	76.1%					
		118 W	224 W	79 W	67 W	25 W
		.328A	2.099A	.585A	.495A	.085A
δ = 0.6	74.3%					
		135 W	237 W	82 W	71 W	25 W
		.406A	2.186A	.485A	.513A	0A
δ = 1.0	71.0%					
		168 W	262 W	88 W	78 W	25 W

1 VOLTAGES REFERENCED TO GROUND

TABLE 4

RECOMPUTED CURRENT & AVERAGE DISSIPATION FOR COLLECTOR DESIGN 3, 5, 82 (HIGH MODE)

	COLLECTOR EFFICIENCY	POLE PIECE 0V[1]	ELECTRODE 1 -13875 V	ELECTRODE 2 -18875 V	ELECTRODE 3 -21975 V	ELECTRODE 4 -24875 V
ONE COMPUTATION RESULTS		.319A	2.024A	.617A	.503A	.127A
δ = 0.4	75.5%	132 W	225 W	73 W	71 W	25 W
		.360A	2.039A	.606A	.500	.085
δ = 0.6	73.9%	149 W	233 W	77 W	74 W	25 W
		.442A	2.068A	.585A	.495A	0A
δ = 1.0	70.8%	183 W	250 W	85 W	82 W	25 W
THREE COMPUTATION APPROXIMATION						
		.288A	2.055A	.635A	.485A	.127A
δ = 0.4	76.1%	118 W	224 W	79 W	67 W	25 W
		.328A	2.099A	.585A	.495A	.085A
δ = 0.6	74.3%	135 W	237 W	82 W	71 W	25 W
		.406A	2.186A	.485A	.513A	0A
δ = 1.0	71.0%	168 W	262 W	88 W	78 W	25 W

1 VOLTAGES REFERENCED TO GROUND

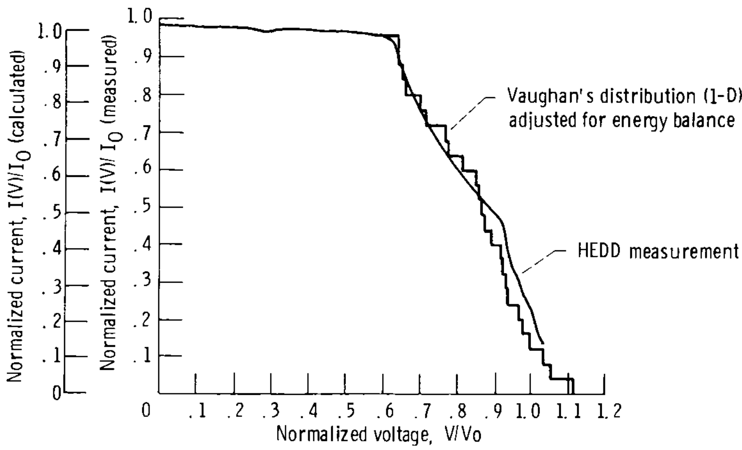

Figure 1. - Low mode spent beam energy distribution.

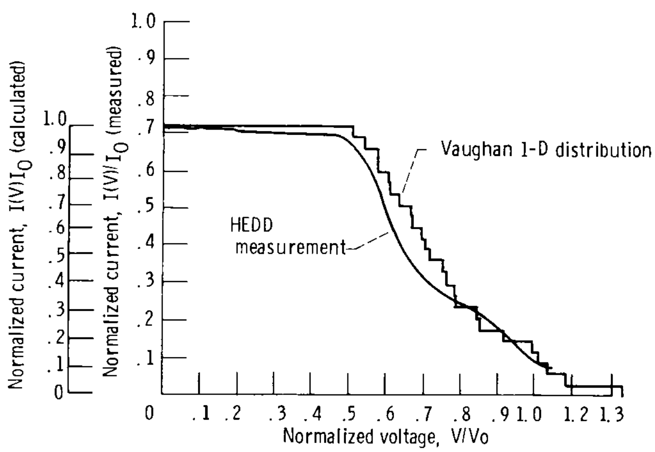

Figure 2. - High mode spent beam energy distribution.

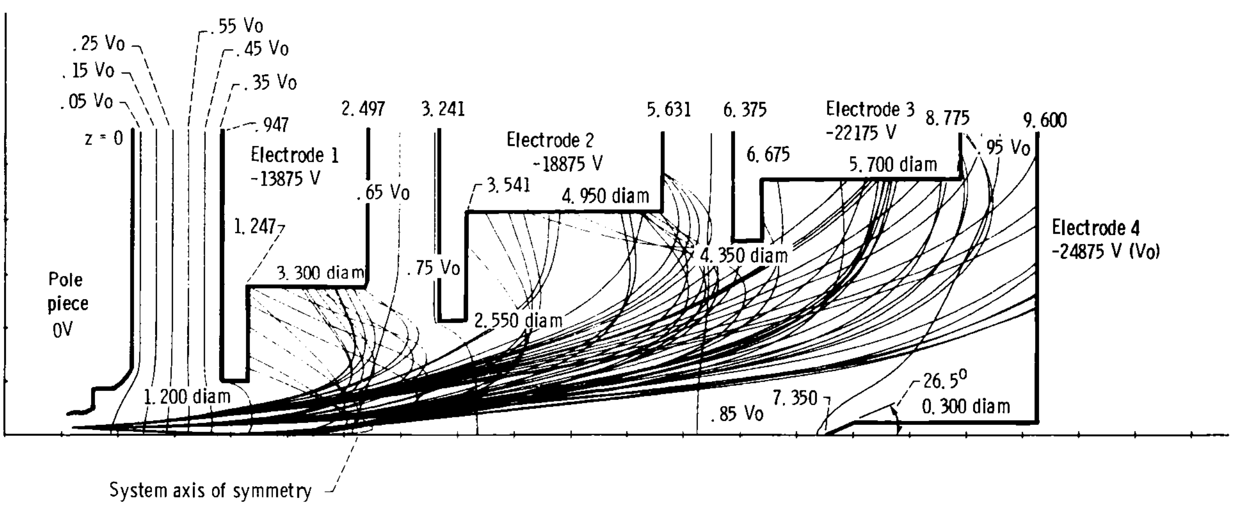

Figure 3. - MDC for F-16, low mode with angles of +3°, -3°, and 0°; dimensions in cm, computed 12, 17, 81.

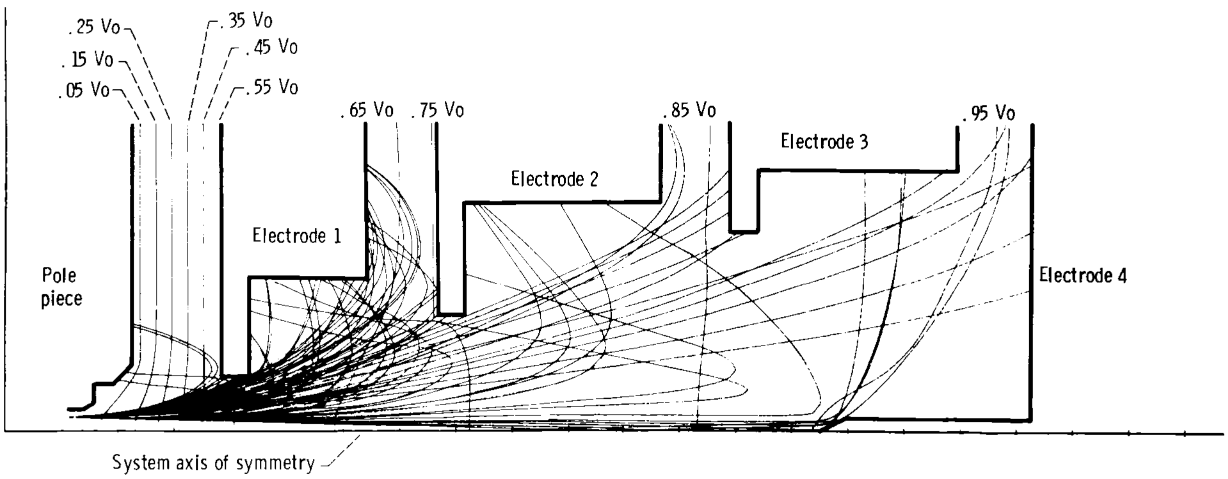

Figure 4. - MDC for F-16, high mode with angles of +3°, -3°, and 0°; computed 12, 17, 81.

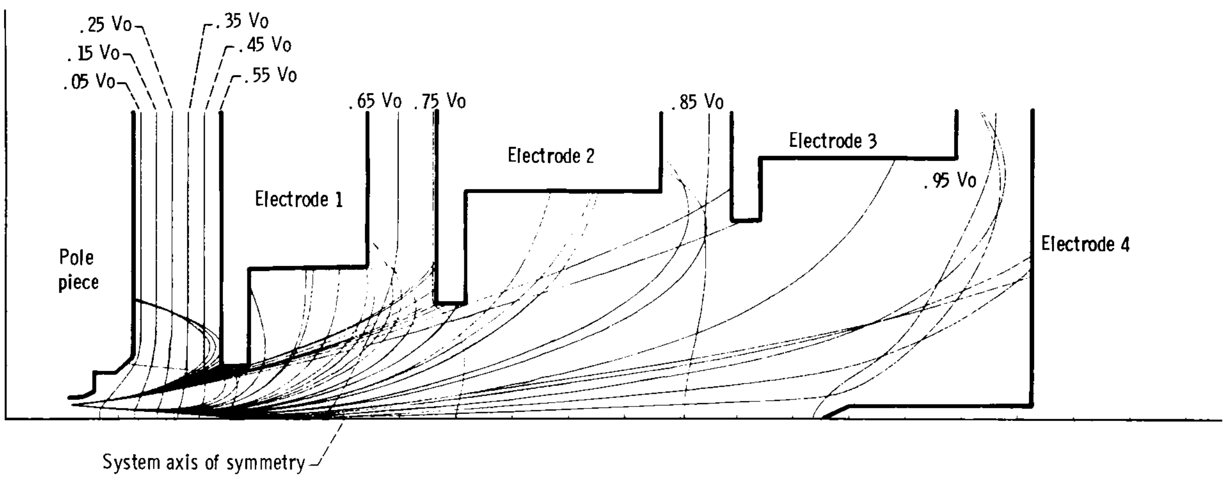

Figure 5. - MDC for F-16, high mode with angles of +6° and -6°, computed 12, 22, 81.

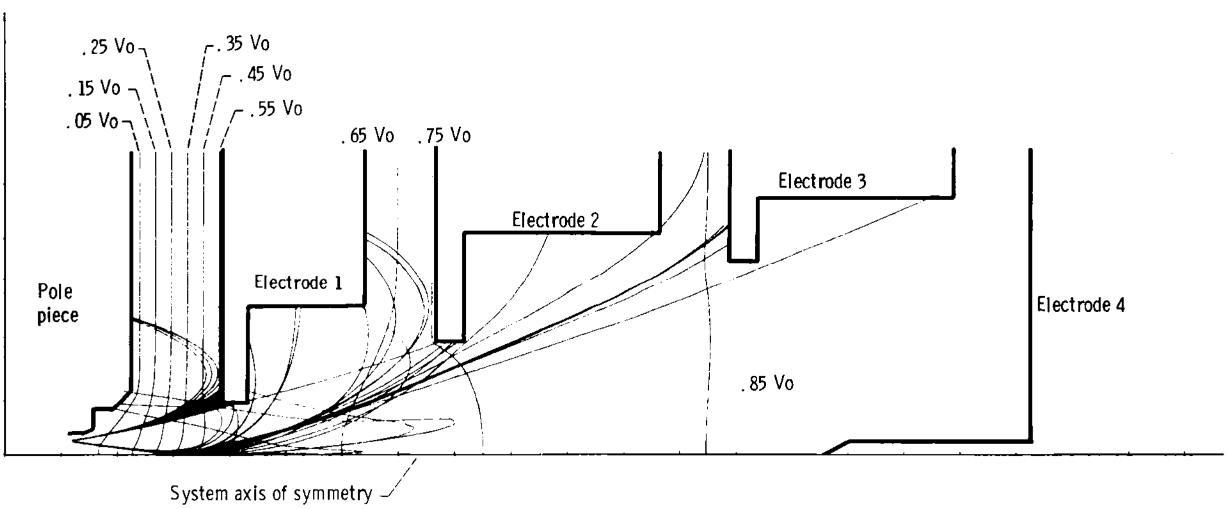

Figure 6. - MDC for F-16, high mode with angles of +9° and -9°, computed 12, 22, 81.

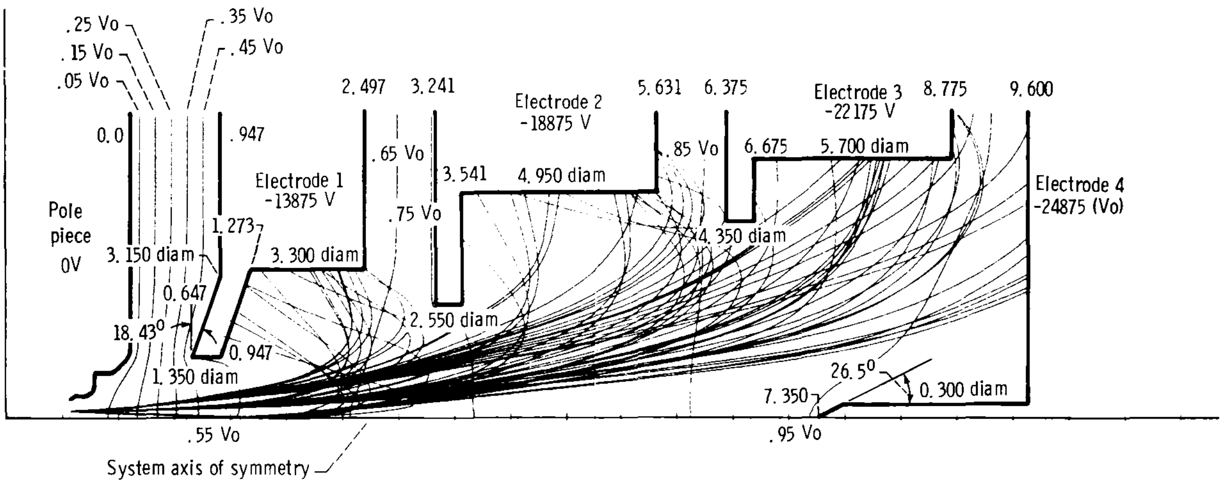

Figure 7. - MDC for F-16, low mode with angles of +3°, -3°, and 0°; dimensions in cm, computed 12, 31, 81.

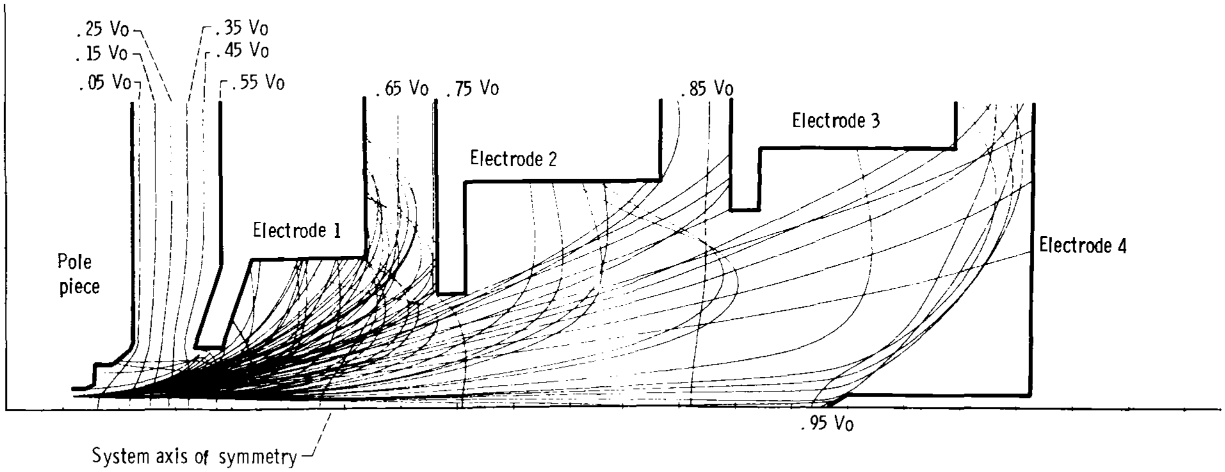

Figure 8. - MDC for F-16, high mode with angles of +3°, -3°, and 0°; computed on 12, 31, 81.

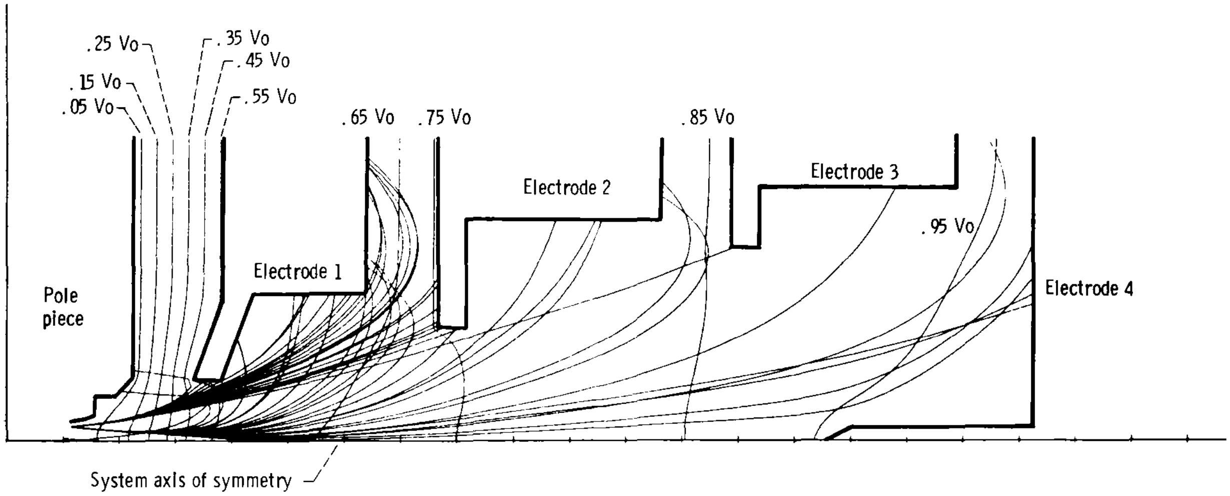

Figure 9. - MDC for F-16, high mode with angles of +6° and -6°, computed on 12, 31, 81.

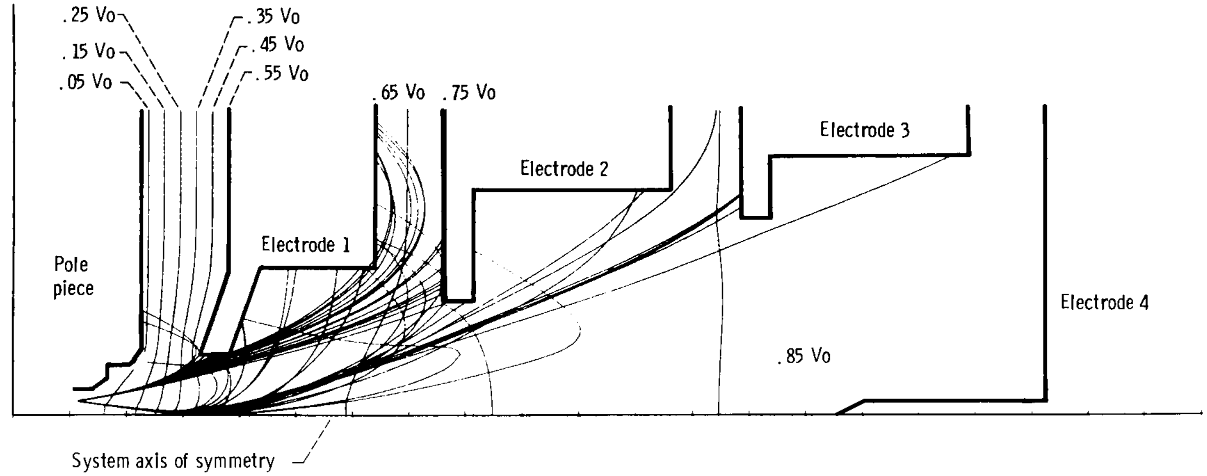

Figure 10. - MDC for F-16, high mode with angles of +9° and -9°, computed on 12, 31, 81.

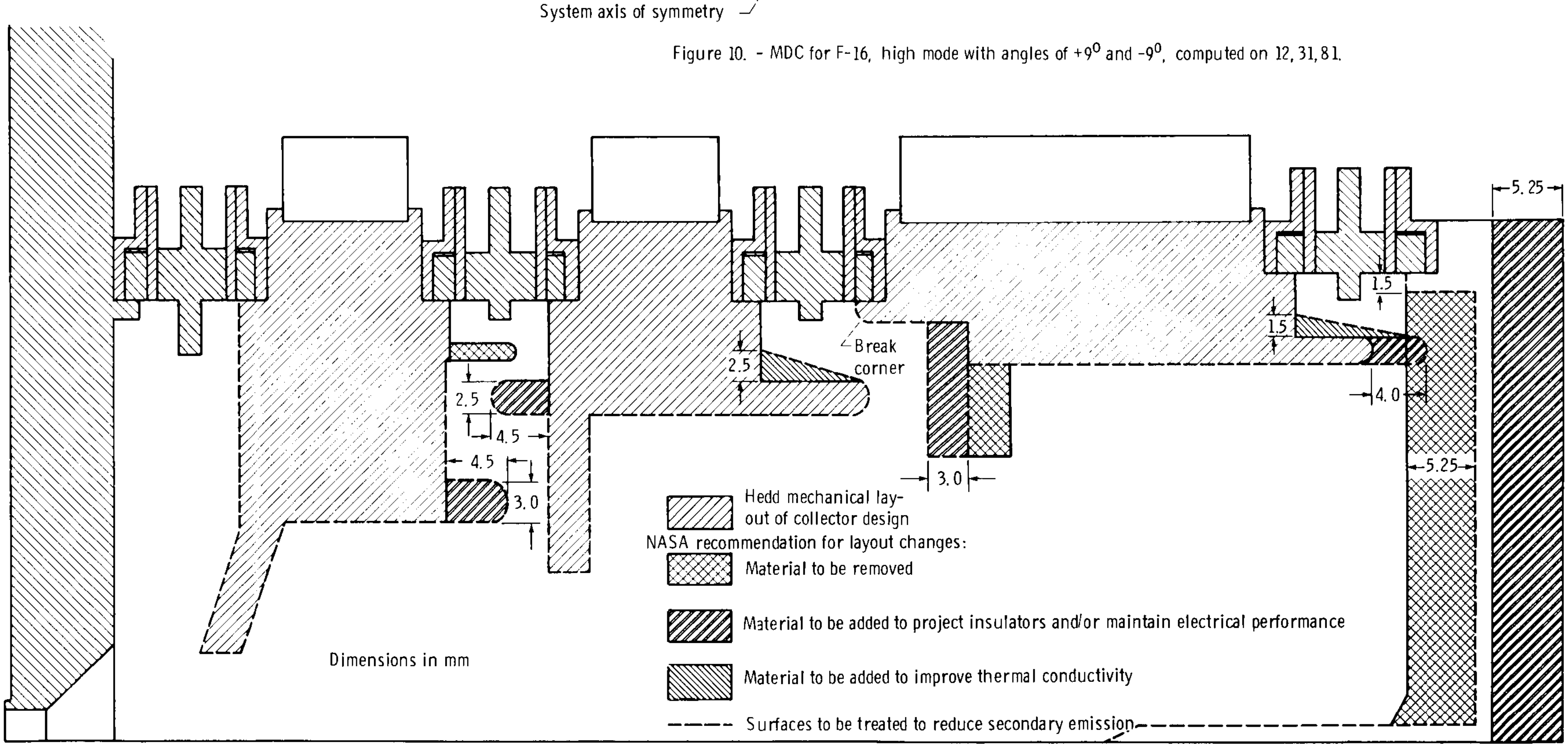

Figure 11. - MDC layout.

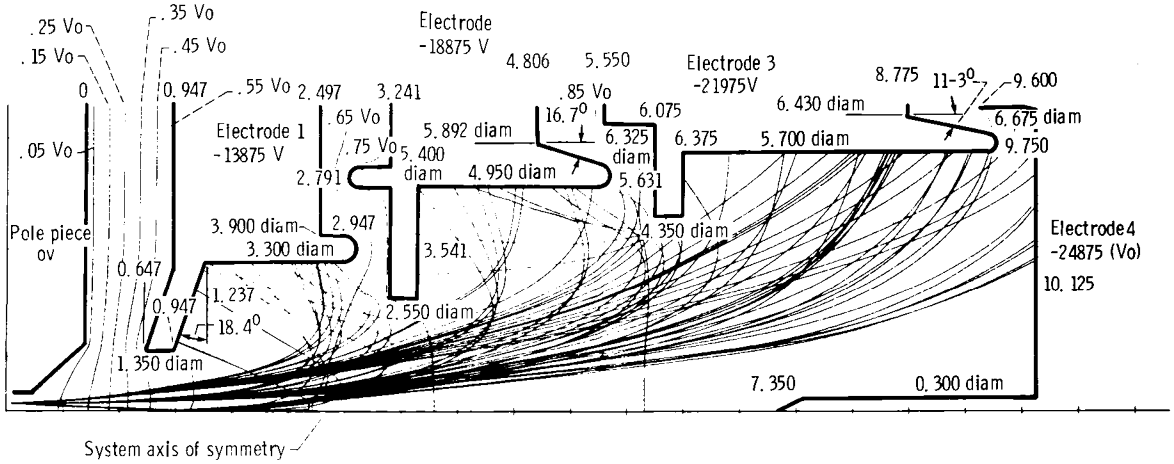

Figure 12. - MDC for F-16, revised layout, low mode with angles of +3°, -3°, and 0°; dimensions in cm, computed 3, 2, 82.

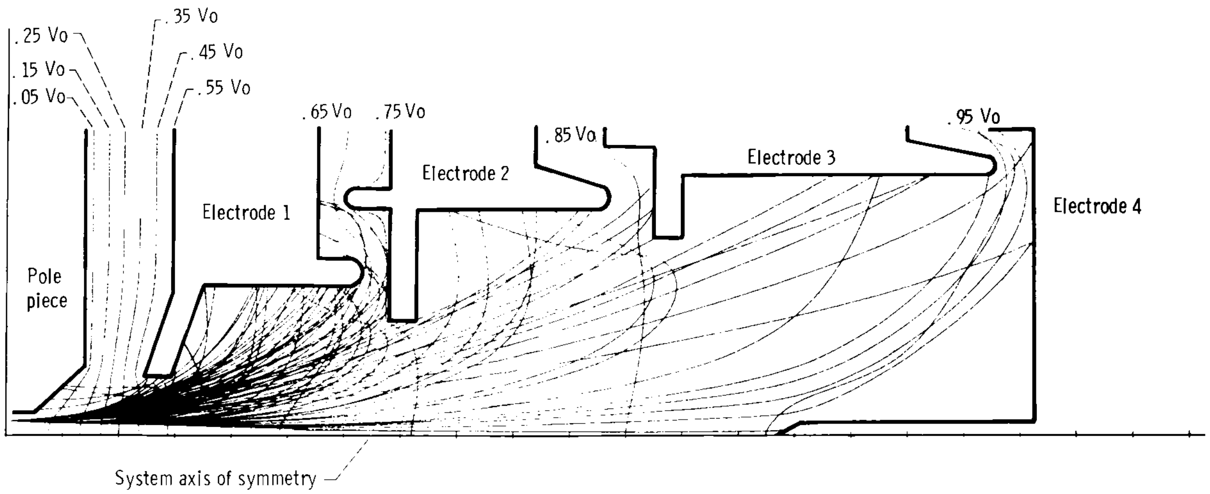

Figure 13. - MDC for F-16, revised layout, high mode with angles of +3°, -3°, and 0°; computed on 3, 5, 82.

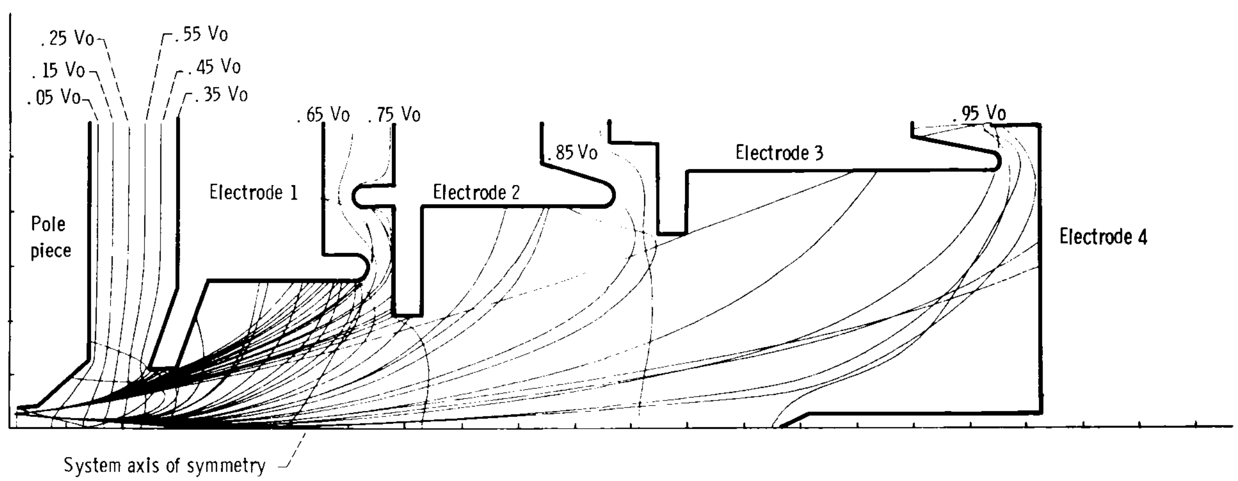

Figure 14. - MDC for F-16, revised layout, high mode with angles of +6° and -6°, computed 3, 5, 82.

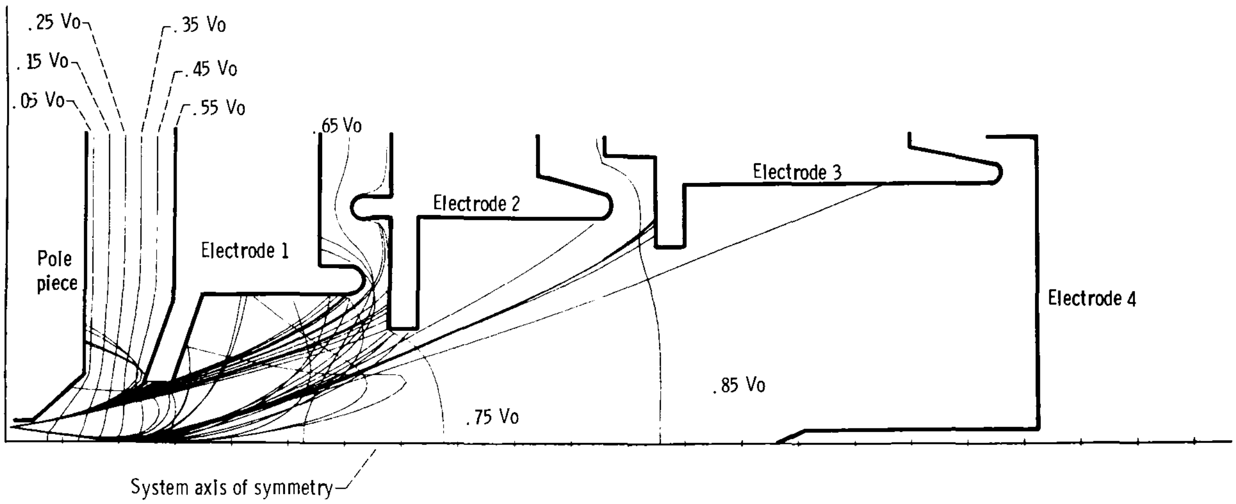

Figure 15. - MDC for F-16, revised layout, high mode with angles of +9° and -9°, computed 3, 5, 82.

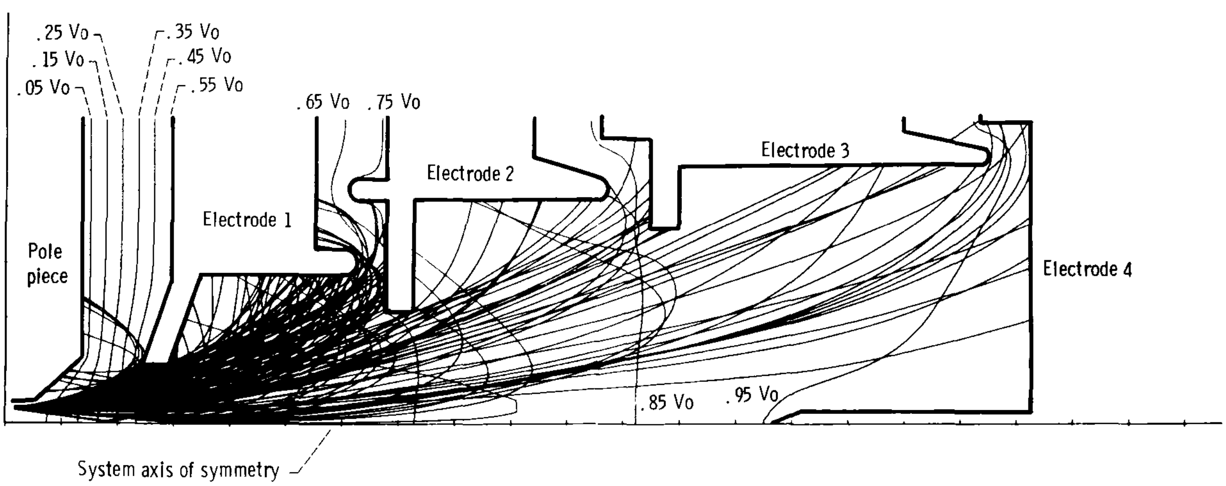

Figure 16. - MDC for F-16, revised layout, high mode with angles of +9°, -9°, +6°, -6°, +3°, -3°, and 0°; computed 4, 28, 82.

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16. Abstract

The design of a multistage depressed collector (MDC) for use with the F-16 Radar Dual Mode Transmitter Tube is described. The methods employed and the rationale on which the design is based are presented in detail. This work was taken on at the request of the Air Force and was carried on with the cooperation of the Electron Dynamics Division of Hughes Aircraft, the manufacturers of the tube.

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