EXPERIMENTAL RESULTS ON THE RCA 7835, AND INITIAL OPERATING PARAMETERS OF THE FTH 515

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With increasing demand for higher proton linac output currents a corresponding increase in 200 megacycle power generation is required. The work done on two separate rf high power sources at Brookhaven will be presented. The first source uses the RCA 7835 super power triode and the other uses the newly developed Thomson-Houston 515 Vapodyne triode.

The resonant cavity for the RCA 7835 triode was constructed by Continental Electronics of Dallas, Texas. Their design is similar to the previous cavity they supplied to Argonne National Laboratory but with a major modification of the output cavity. Our cavity can be pressurized up to 60 psig and the output transmission line is of the coaxial line type instead of a rectangular guide. Use of the coaxial line enabled us to incorporate the ability to vary the loading on the tube.

The cavity is shown in Fig. 1. The top section of the cavity is almost identical to the Argonne cavity. This section houses the tuned input drive cavity as well as the fixed tuned output slave cavity. The rf drive input loading and tuning are varied by means of mechanized drives. The bottom section of the cavity contains the fixed tuned input slave cavity as well as the output tuned cavity. In Fig. 2 it is seen that the 9-in. output line can travel a distance of 5 in. along the length of the output coaxial resonator. (The loading position cannot be moved while the cavity is pressurized.) The resonator tuning is accomplished by sliding shorts that can travel 8 in. along the cavity length. The pressure vessel encloses both the upper and lower output cavity and dc blockers. Gas barriers are provided for in both the input driving cavity and the 9-in. output line.

Figure 3 shows a simplified drawing of the output cavity. The upper irrathene dc blocker functions as an open-ended coaxial line forming a half wavelength termination for the triodes upper output cavity section. The lower irrathene dc blocker forms a quarter wavelength open-ended circuit that electrically joins the tube grid-plate output cavity with the external output cavity. Both dc blockers withstood dc hi-pot tests of 70 kilovolts. To perform this test both blockers were mounted in the pressure vessel with the cavity pressurized at 7.5 psig. Pressurization was required to eliminate voltage breakdown traveling in air paths around the blocker.

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An approximate transmission line equivalent circuit of the lower output cavity (supplied by Continental Electronics) is shown in Fig. 4a. The junction of the 9.5 ohm and 26.8 ohm lines represents the interface between the tube's internal cavity and the external cavity. By use of this equivalent circuit the voltage distribution along the cavity was calculated. (See Appendix par. 1.0). Figure 4b shows this distribution when an effective loading of 40 ohms on the tube was assumed. Figure 4c shows this distribution for a loading of 65 ohms. In both cases the terminating impedance on the 9-in. output line was 50 ohms. It is seen that the voltage maximum is located in the 25-ohm section and the voltage minimum in the 9.5-ohm section. From these calculations the position of the loading and tuning shorts are also located. Figure 5 shows these locations. Notice that the sliding short position is essentially the same for both loadings. The position of the loading moves about 2 in. or .035 wavelengths.

Input driving power for testing of the 7835 system was supplied by an RCA A2515D tetrode. The 7835 high power resistive load was built by Continental Electronics and -50db directional coupler was supplied by Dielectric Products. The dummy load cooling water was used to make calorimetric power measurements. The directional coupler power measurements which were approximately 3% lower than the calorimetric readings, provided a good cross check.

Input matching to the drive cavity was very good. Tuning is fairly broad. The loading position was not ideal since it was only an inch away from its lowest position. Test results on the output cavity for various positions of loading are given in Fig. 6. It is to be noted that at the extreme lowest position of loading, the highest effective impedance seen by the tube is 49 ohms. Since the optimum impedance for the 7835 tube is 58 ohms it is seen that the loading position tuning range is insufficient (See Appendix par. 2.0). This cavity is ideal for the RCA 4617 (matrix oxide cathode version of 7835) for its optimized impedance is 40 ohms. The peak power output obtained was 5.4 megawatts (calorimetric measurement). The dc plate voltage was 33 kilovolts and the dc peak plate current was 300 amps. To obtain this output the cathode current had to be pushed to 6900 amperes at 4.1 volts. Evidence of cathode emission limitation was noted since the power output dropped sharply if the cathode current was lowered. Since RCA's maximum ratings are 300 amps dc plate current and 7000 amp at 4.2 volts for the cathode, it was decided not to push the tube any further. The loading and tuning positions are shown in Fig. 7.

A modification to the present cavity is under consideration. Part of the output cavity circuit is comprised of a .1 wavelength line of 9.5 ohm characteristic impedance. By use of the SMITH chart it was estimated that if this line's characteristic impedance was increased to 19.3 ohms the loading position would tend to move up by 4.1 in. (.07 wavelengths). (See Appendix par. 3.0). Mechanically this is easily done since all it entails is sweating off a few pieces of cylindrical stock used to build up the radius in this line. To physically extend the loading position further down would require lengthening the pressure vessel which would be a major job. Presently we are trying to load the tube with a higher external impedance. The approach here is to use the Continental 50-ohm load which is comprised of two sections; a resistive section and a matching section. By eliminating the matching section and with proper lengths of coax line an external impedance of 70 ohms can be connected to the cavity (Resistive section has VSWR of 1.4).

This would enable us to run higher voltages without exceeding the operating current on the tube. It would also subject the cavity to higher peak voltages.

If the tube was pushed to RCA's maximum ratings of 300 amps plate current and 40 kilovolts plate voltage, 7 megawatts could be obtained with an effective resistance of 63.6 ohms. (See Appendix par. 2).

Up to this point the cavity has shown no tendency toward voltage breakdown but it has not been subjected to a resonant cavity load. One set of spring ring contacts for filament current burned up but since replacement there were no more troubles. To replace a tube in the cavity would take approximately 3.5 hours.

In the future it is intended to subject this tube to a resonant cavity load. The tuning on the output cavity is quite sharp and I am a little apprehensive of detuning effects of a cavity.

In addition to the experimental evaluation of the RCA 7835 the final stages of the linac operating rf drive system were modified. The Thomson-Houston 470 triodes were replaced by Thomson-Houston 515 triodes. Figure 8 shows a comparison of the typical operating conditions. Basically the 515 is a 470 with increased cathode surface. Its potential output power is 4 megawatts as opposed to 2.3 megawatts for the 470. The average plate dissipation has been increased from 10 to 65 kilowatts. As with the previous 470 tubes the output of the final two 515 stages are summed in a magic tee before being coupled to the linac. There was insufficient time to check the performance of these tubes into a resistive load. They were designed to fit into the 470 cavities with only minor modifications. The filament transformers were replaced but the output coupling loops were left the same. The output power from each tube is approximately 2.8 megawatts at 30 kV impressed plate voltage for a total of 5.6 megawatts into the linac tank. Cavity output loops were not optimised due to the time restriction. Instead tuners available on the magic tee were used to load the tube as best as possible. There were also indications that the power output was being limited by insufficient drive. Nevertheless the modification was very successful since it increased our beam loading capability from 25 mils to at least 40 mils.

With improvements on the output coupling and more drive this system should be able to accommodate 65 to 70 mil beams. The tubes have been in operation now for 2200 hours. One of the tubes showed a tendency toward voltage breakdown from the plate to grid. The 515 tube has neither the peak power output nor the power gain of the RCA 7835, but it is quite a bit cheaper.

Appendix

1.0 Determination of Loading Position and Voltages in the Output Cavity.

An effective load impedance at the center of the tubes grid-plate region is assumed. By use of the Smith chart the position of a 50-ohms external load in the cavity is determined that corresponds to the assumed loading. The equivalent circuit of Fig. 4a was used and calculations were made for assumed resistances of 40 and 65 ohms.

1.1.0 Smith Chart 1

Z'_x = normalized impedance on transmission line of characteristic impedance X.

pt. 0 and 0' normalized impedance at tube center.

pt 0 $Z'_5 = \frac{40}{5} = 8$ ohms when effective loading of 40 ohms is assumed.

pt 0' $Z'_5 = \frac{65}{5} = 13$ ohms when effective loading of 65 ohms is assumed.

pts 1 & 1' values of Z'_5 at 26.8 and 5-ohm line junction.

(rotation of $.05\tau$)

pt 1 $Z'_5 = 1.2 + J2.6$

pt 1' $Z'_5 = .8 + J2.9$

pts 2 & 2' are impedance of pts 1 and 1' normalized to 26.8 ohms

pt 2 $Z'_{26.8} = .224 + J.485 = Z'_5\ (.187)$

pt 2' $Z'_{26.8} = .149 + J.54$

pts 3 & 3' values of $Z'_{26.8}$ at 9.5 and 26.8 ohm line junction (rotation of $.06\tau$)

pt 3 $Z'_{26.8} = .18 + J.075$

pt 3' $Z'_{26.8} = .12 + J.12$

pts 4 & 4' impedance of pts 3 & 3' normalized to 9.5 ohms.

pt 4 $Z'_{9.5} = (2.82)\ Z'_{26.8} = .507 + J.211$

pt 4' $Z'_{9.5} = .339 + J.339$

pts 5 & 5' values of $Z'_{9.5}$ at 19.3 and 9.5 ohm line junction (rotation of $.102\tau$)

pt 5 $Z'_{9.5} = .54 - J.3$

pt 5' $Z'_{9.5} = .32 - J.26$

pts 6 & 6' impedance of pts 5 & 5' normalized to 19.3 ohms

pt 6 $Z'_{19.3} = (.483)\ Z'_{9.5} = .266 - J.148$

pt 6' $Z'_{19.3} = .158 - J.128$

pts 7 & 7' values of $Z'_{19.3}$ at 25 and 19.3 ohm line junction (rotation of .11852)

pt 7 $Z'_{19.3} = .61 - J1.06$

pt 7' $Z'_{19.3} = .36 - J1.12$

pts 8 & 8' impedance of pts 7 & 7' normalized to 25 ohms

pt 8 $Z'_{25} = (.77)\ Z'_{19.3} = .47 - J.82$

pt 8' $Z'_{25} = .278 - J.865$

pts 9 & 9' rotation of pts 8 and 8' to the real axis which is the point of maximum voltage on the line.

pt 9 was rotated $.13\tau$ and $Z'_{25} = 3.8$ ohms

pt 9' was rotated $.133\tau$ and $Z'_{25} = 6.4$ ohm

1.1.1 Smith Chart 2

At this point it was decided to work in admittances, Y'_{25}, instead of impedances, Z'_{25},

pts 10 & 10' are the admittance values of pts 9 & 9'.

In order to obtain the assumed loading points on the tube, the constant reflection coefficient circle that points 10 and 10' lie on must intercept the .5 ohm resistive circle, since at the loading point on the line the admittance must be

$$Y'_{25} = \frac{50}{25} + JX$$

where: $\frac{50}{25}$ is the normalized conductance of the 50 ohm external load; JX is the susceptance due to the sliding short

pts 11 & 11' are the intercepts of the .5 ohm resistive circle

pt 11 is a rotation of $.126\ \tau$ from voltage max.

pt 11' is a rotation of $.158\ \tau$ from voltage max.

Therefore, the loading position is determined.

pt 11 (40 ohm loading) is .126 + .13 = $.256\tau$ from 25 and 19.3 ohm line junctions.

pt 11' (65 ohm loading) is .158 + .13 = $.291\tau$ from 25 and 19.3 ohm line junctions.

The location of the short is determined by the value of susceptance at points 11 & 11'

for pt 11 the short is .250 - .126 = $.124\tau$ away from the 50 ohm loading position.

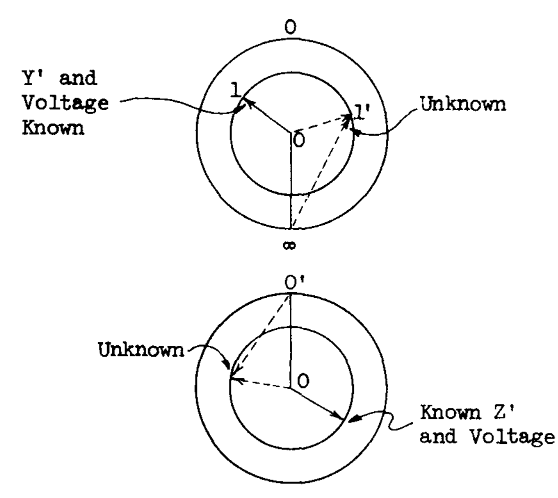
for pt 11' the short is .250 - .158 = $.092\tau$ away from the 50 ohm loading position.

See Figure 5

1.2 Voltage Distribution Along Cavity

The peak voltage distribution for tube loadings of 40 and 65 ohms are found by use of Smith charts 1 and 2. Peak voltage was determined for the case where 7 megawatts was delivered to the output load.

If the voltage at one point in a transmission line is known the voltage at any other point can be found by use of the Smith chart.



METHOD

(a) Determine voltage scale such that distance 0'-1 is set equal to voltage at point known
(b) Rotate radius 01 to point on line where voltage is to be determined
(c) Measure new distance 0'1' to unknown voltage point
(d) The voltage at unknown point can be found by plotting distance found in step C on voltage scale of step 2

Note: At a junction point of lines of different characteristic impedance the voltage is continuous, but normalized impedances are different, thus, a new voltage scale has to be determined when crossing the junction.

1.2.1 Voltage Distribution for 40 ohm Loading

$(V\ peak)^2 = 2\ Pout\ Rout = 2\ (50)\ 7 \times 10^6 = 7 \times 10^8$

V peak = 26.4 kilovolts across 50 ohm load

See Voltage Scale Fig. 9 and Smith charts 1 and 2

1st Scale

$V_o = 26.4^{kV}$ point 11 on Smith chart

$V_{max} = \frac{13.9}{10} \times 26.4^{kV} = 36.7$ kilovolts (pt 9)

where $\frac{13.9}{10}$ is determined from scale

$V_1 = \frac{9.9}{10} \times 26.4^{kV} = 26.1$ kilovolts is voltage at 19.3 and 25 ohm junction (pt 8)

2nd Scale

$V_2 = V_1 = 26.1$ kilovolts thus new scale determined (pt 7)

$V_3 = \frac{4.3}{11.1} \times 26.1^{kV} = 10.15$ kilovolts at 9.5 and 19.3 ohm junction (pt 6)

3rd Scale

$V_4 = V_3 = 10.15$ kilovolts (pt 5)

$V_5 = \frac{6.3}{6.9} \times 10.15^{kV} = 9.26$ kilovolts at 26.8 and 9.5 ohm junction (pt 4)

4th Scale

$V_6 = V_5 = 9.26$ kilovolts (pt 3)

$V_7 = \frac{7.1}{2.9} \times 9.26^{kV} = 22.7$ kilovolts (pt 2)

5th Scale

$V_8 = V_7 = 22.7$ kilovolts (pt 1)

$V_9 = \frac{15.6}{14.8} \times 22.7^{kV} = 23.9$ kilovolts (pt 0) voltage at tube center

1.2.2 Voltage Distribution for 65 ohm Loading

See Voltage Scale Fig. 10 and Smith charts 1 and 2.

1st Scale

$V_o = 26.4$ kilovolts point 11' on Smith chart

$V_{max} = \frac{15.2}{8.6} \times 26.4^{kV} = 46.7$ kilovolts (pt 9')

$V_1 = \frac{10.4}{8.6} \times 26.4^{kV} = 31.9$ kilovolts (pt 8') voltage at 19.3 and 25 ohm junction

2nd Scale

$V_2 = V_1 = 31.9$ kilovolts thus new scale determined (pt 7')

$V_3 = \frac{3.1}{11.7} \times 31.9^{kV} = 8.45$ kilovolts at 9.5 19.3 ohm junction (pt 6')

3rd Scale

$V_4 = V_3 = 8.45$ kilovolts (pt 5')

$V_5 = \frac{6.1}{5.4} \times 8.45^{kV} = 9.55$ kilovolts at 26.8 and 9.5 ohm junction (pt 4')

4th Scale

$V_6 = V_5 = 9.55$ kilovolts (pt 3)

$V_7 = \frac{7.8}{2.6} \times 9.55^{kV} = 28.6$ kilovolts at 5 and 26.8 ohm junction (pt 2')

5th Scale

$V_8 = V_7 = 28.6$ kilovolts (pt 1')

$V_9 = \frac{16.3}{15.5} \times 28.6^{kV} = 30.1$ kilovolts (pt 0') voltage at tube center

2.0 Effective Loading Resistance for RCA 7835 and RCA 4617 Tubes.

Class B operation has been assumed and the plate voltage swing was not allowed to go below 10 kilovolts.

E_b = dc plate voltage

I_b = Average value of plate current

I_{bm} = Peak value of plate current

I_{pi} = Fundamental component of plate current (RMS)

E_{pi} = Fundamental component of plate voltage (RMS)

P_o = Power output

P_i = Power input

2.1 Resistance for 7835 Under Typical Operation From RCA data sheet

E_b = 34 kilovolts, I_b = 265 amp, P_o = 5 megawatts

$$E_{pi} = \frac{(34-10)\ 10^3}{1.414} = 17 \text{ kilovolts}$$

$$I_{pi} = 1.11\ I_b = (1.11)\ (265) \doteq 294 \text{ amps}$$

$$R_o = \frac{E_{pi}}{I_{pi}} = \frac{17 \times 10^3}{294} = 57.8 \text{ ohms}$$

Desired resistance is 57.8 ohms

2.2 Resistance for 4617 Under Typical Operation From RCA data sheet

E_b = 35 kilovolts, I_b = 400 amp, P_o = 8 megawatts

$$\therefore E_{pi} = \frac{(35\ -\ 10)\ 10^3}{1.414} = 17.6 \text{ kilovolts}$$

$$I_{pi} = 1.11\ I_b = (1.11)\ (400) = 444 \text{ amps}$$

$$R_o = \frac{E_{pi}}{I_{pi}} = \frac{17.5 \times 10^3}{444} = 40 \text{ ohms}$$

2.3 Resistance for 7835 When at Maximum Ratings From RCA data sheet

E_b = 40 kilovolts, I_b = 300 amps

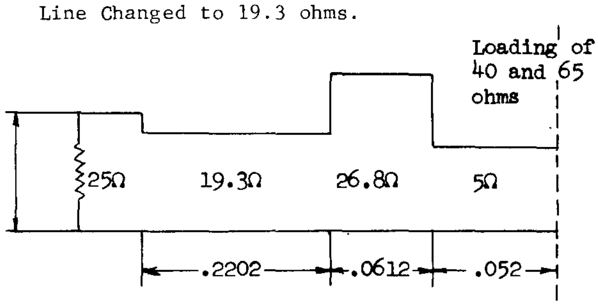
$$E_{pi} = \frac{(40-10)\ 10^3}{1.414} = 21.2 \text{ kilovolts}$$

$$I_{pi} = 1.11\ I_b = (1.11)\ 300 = 333 \text{ amps}$$

$$R_o = \frac{E_{pi}}{I_{pi}} = \frac{(21.2)\ 10^3}{333} = 63.6 \text{ ohms}$$

$$P_{out} = I_{pi}E_{pi} = (21.2)\ (333)10^3 = 7.0$$ megawatts

3.0 Determination of Loading Position if 9.5 ohm Line Changed to 19.3 ohms.



The impedances, $Z'_{26.8}$, at 26.8 and 19.3 ohm line junction were determined in paragraph 1.0 of Appendix see Smith chart 3.

pt. 3 $Z'_{26.8} = .18 + J.075$

pt. 3' $Z'_{26.8} = .12 + J.12$

pts. 4 & 4' are impedances of pts 3 & 3' normalized to 19.3 ohms.

pt 4 $Z'_{19.3} = (1.39)\ Z'_{26.8} = .25 + J.104$

pt 4' $Z'_{19.3} = .167 + J.167$

pts 5 & 5' values of $Z'_{19.3}$ at 25 and 19.3 ohm line junction (rotation of .22τ)

pt 5 $Z'_{19.3} = 1.65 - J1.83$

pt 5' $Z'_{19.3} = 1.1 - J2.22$

pts 6 & 6' are impedances of pts 5 & 5' normalized to 25 ohms

pt 6 $Z'_{25} = (.77)\ Z'_{19.3} = 1.27 - J1.41$

pt 6' $Z'_{25} = .847 - J1.71$

pts 7 & 7' rotation of pts 6 & 6' to voltage maximum

pt 7 was rotated .0655τ

pt 7' was rotated .073τ

pts 8 & 8' are values of Y'_{25} instead of Z'_{25}

pts 9 & 9' are the intercepts of the .5 ohm resistive circle

pt 9 is a rotation of .115τ from voltage max.

pt 9' is a rotation of .149τ from voltage max.

Therefore, the loading position is determined

pt 9 (40 ohm loading) is .115 + .0655 = .1805τ from 25 and

19.3 ohm line junction

pt 9' (65 ohm loading) is .149 + .073 = .222τ from 25 and 19.3 ohm line junction

See Fig. 7.

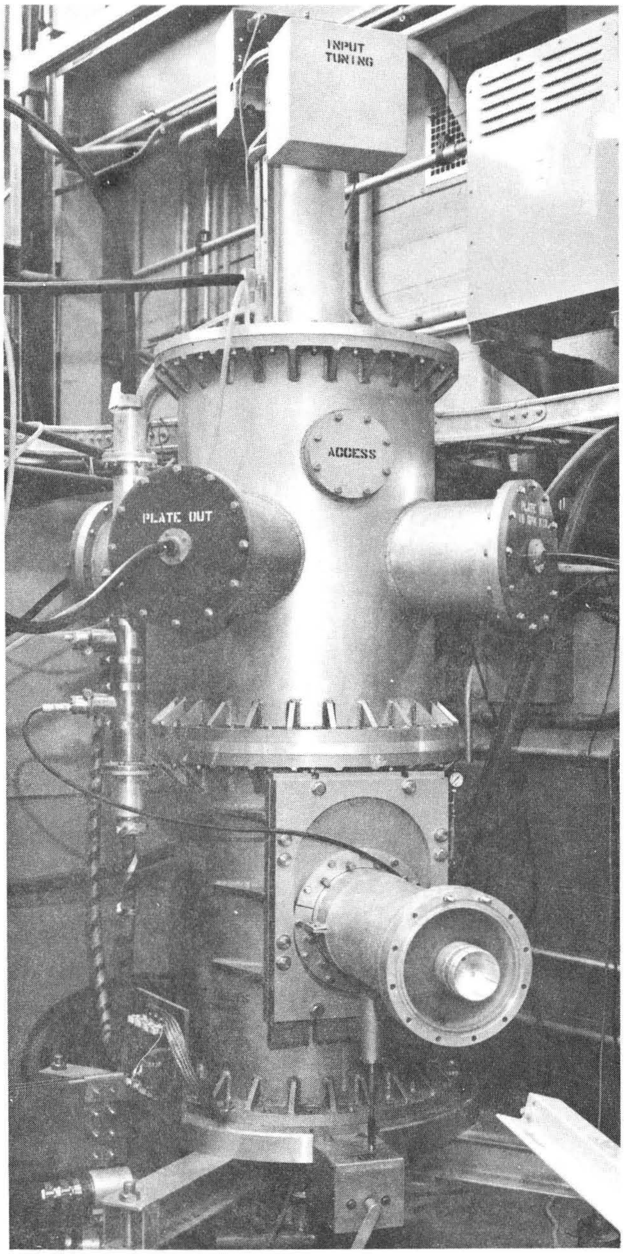


Fig. 1. 7845 rf cavity.

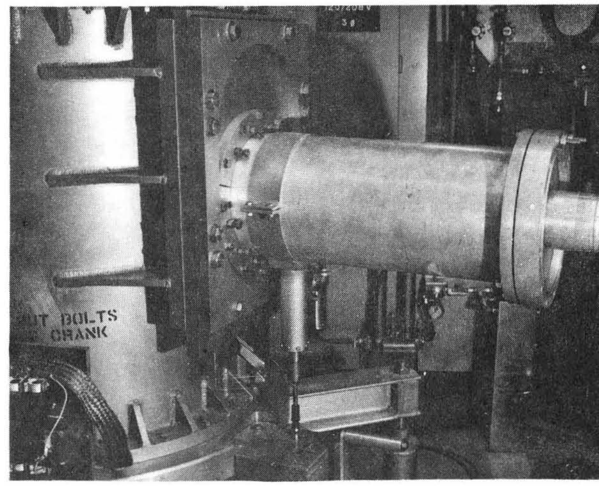


Fig. 2. Variable loading.

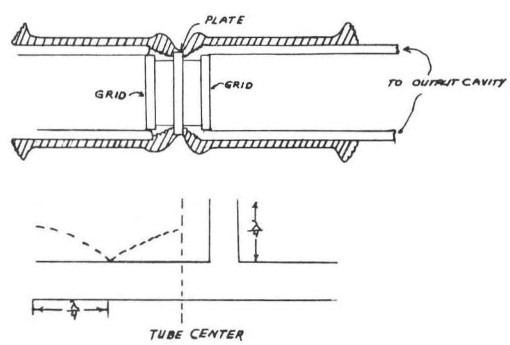


Fig. 3. Sketch of output cavity.

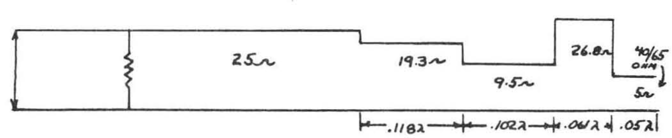


Figure 4A

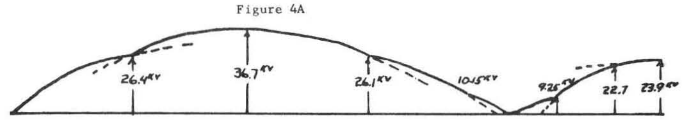


Figure 4B

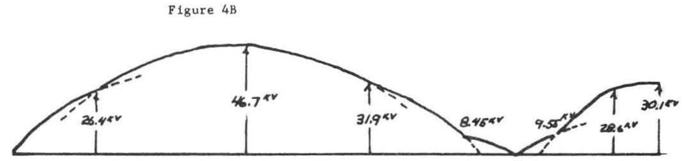


Figure 4C

Fig. 4. a. Equivalent circuit.
b. Voltage distribution--40 ohm loading.
c. Voltage distribution--65 ohm loading.

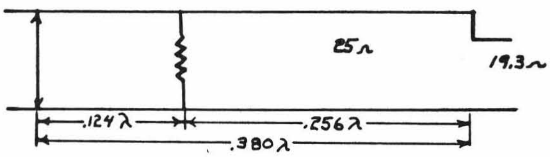


Figure 5A

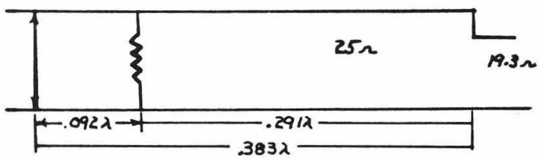


Figure 5B

Fig. 5. a. Loading position--40 ohm.
b. Loading position--65 ohm.

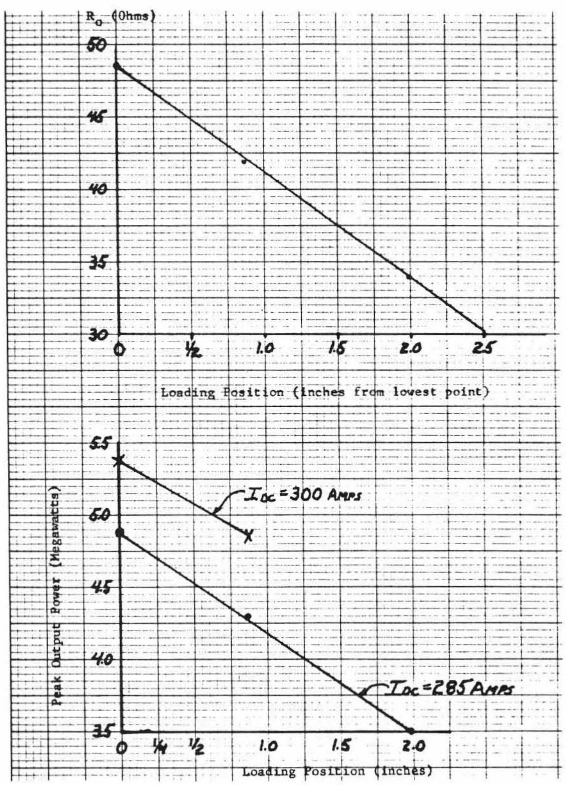
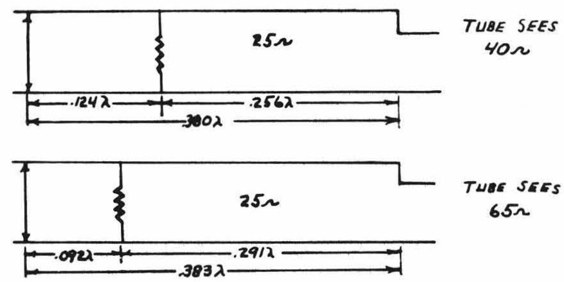
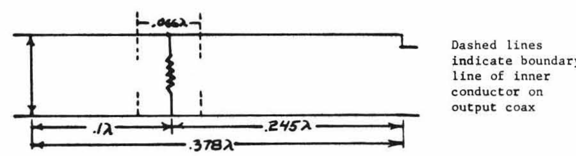


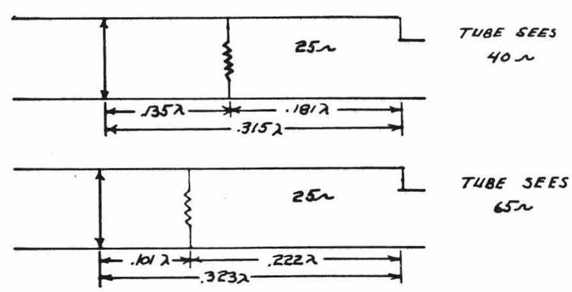
Fig. 6. Test results on 7835 system.



Calculated Positions of Loading



Actual Position of Loading (centerline of coax output as reference)



Calculated Positions for Modified Unit

Fig. 7. Loading positions.

TYPICAL OPERATION	TH515	TH470
DC Plate Voltage	37 kV	37 kV
DC Grid Bias	-650 V	-650 V
Average Plate Current (Pulse)	200 amp	130 amp
Peak Drive Power	0.7 MW	340 kW
Peak DC Plate Power	7.4 MW	4.8 MW
Average Dissipation	7 kW	.5 kW
Peak Output Power	4 MW	2.35 kW
Frequency	200 Mc	200 Mc

Fig. 8. Typical data.

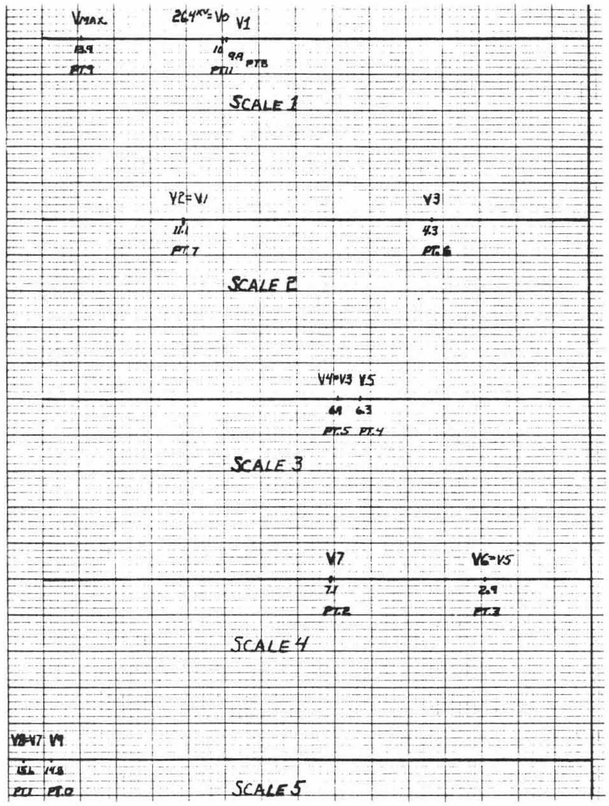


Fig. 9. Voltage distribution for 40 Ω loading.

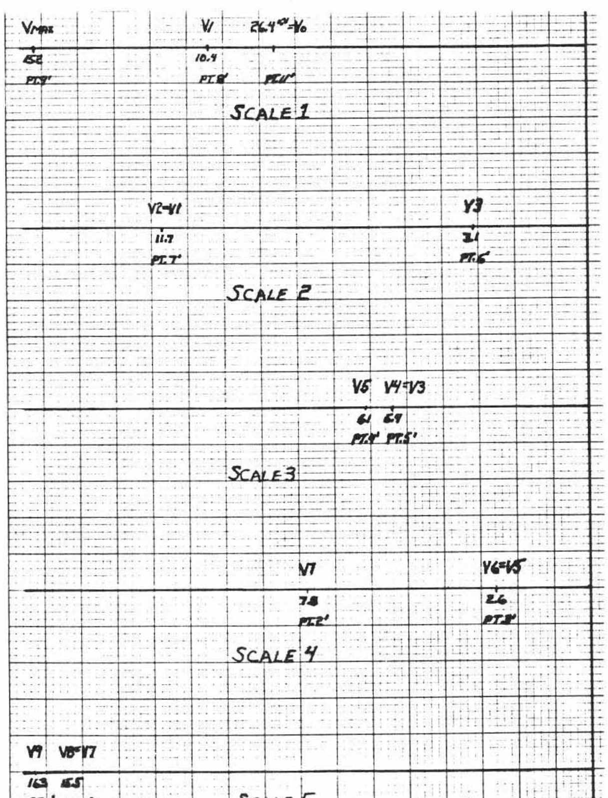
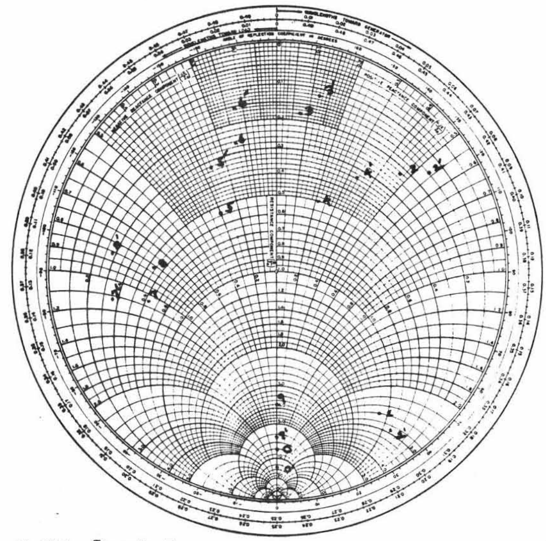
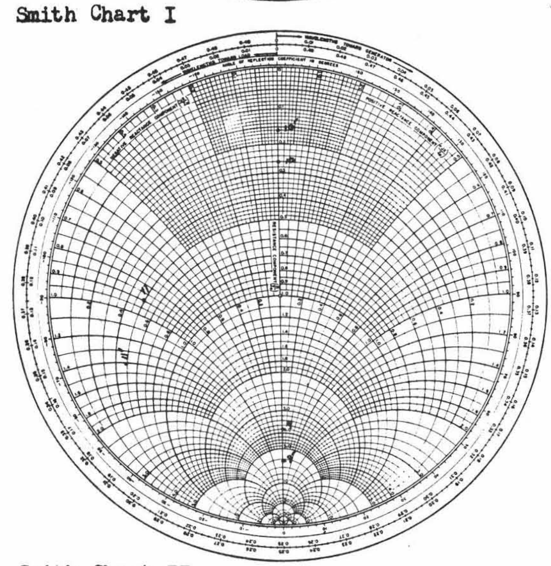


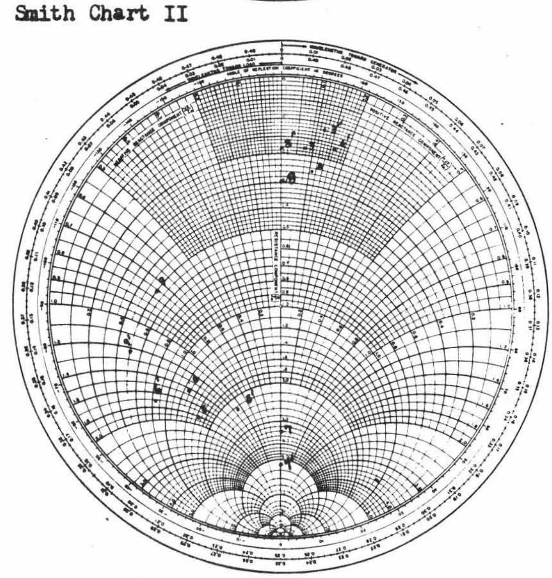
Fig. 10. Voltage distribution for 65 Ω loading.



Smith Chart I



Smith Chart II



Smith Chart III