DEVELOPMENT OF A 100 WATT S-BAND TRAVELING-WAVE TUBE

By

L. A. Roberts
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27 October 1967

Contract No. 951299

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Quarterly Report No. 5

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ABSTRACT

This report is the fifth quarterly progress report on the development of the WJ-395, a 100 watt, 55 percent efficiency, 2.3 GHz traveling-wave tube for space applications. During this quarter, the effects of peak magnetic field strength and magnet period were tested on Tube S/N 6. Tube S/N 7 was built and tested. It was found that its performance was below that expected for the design change incorporated in this tube. From the performance tests it was reasoned that helix loss in the output section had led to the reduced efficiency.

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I. INTRODUCTION

Purpose and Goals of the Project

The purpose of this program is to develop a high efficiency, 100 watt, 2.3 GHz traveling-wave tube suitable for use in space. The tube has been designated the WJ-395. The most important goal of the program, requiring an advance over present techniques, is the achievement of high efficiency. The basic performance goals are a power output of 100 watts at an overall efficiency of 55 percent and a gain of 30 dB. Other requirements dictate conduction cooling and the ability to perform through launch and under space environment conditions.

Direction of Program Development

The program has proceeded through an initial stage where the basic electrical and mechanical design of the WJ-395 was worked out. It was shown that the thermal design of the tube was adequate from the RF power handling standpoint since power levels up to 140 watts output were demonstrated. It was found that the original collector design was inadequate and a new one was designed, constructed and tested.

The new collector was found capable of adequately handling the beam power with satisfactory hotspot temperatures. The mechanical design of the tube was determined to be adequate from the vibration standpoint. Not only did it demonstrate low incidental phase modulation but it also did not develop any mechanical fatigue as a result of a long period of high level random vibration.

From the standpoint of efficiency improvement, an abortive attempt was made to build a two helix tube. This made very clear the electrical and constructional difficulties associated with type of device. It pointed up the advantages of the single helix with a single helix voltage. In the meantime, real advances had been made in efficiency performance with single helix tubes on a program sponsored by the U.S. Army Electronics Command. An understanding of the controlling factors on efficiency began to emerge from the company sponsored high efficiency research program. The above types were solenoid focused and operated near 1.0 GHz at a power level of 20 watts. These designs were scaled to our required frequency and power range and adapted to PPM focusing. They resulted in a tube which delivered 102 watts at an overall efficiency of 44.5 percent and 70 watts at an overall efficiency of 45.7 percent.

The remainder of the program will explore efficiency improvement using single helix techniques including the "positive taper."

II. EXPERIMENTAL PROGRAM

WJ-395 S/N 6

Further measurements have been made on this tube during the quarter to explore various effects of operating parameters on the efficiency, gain and power output performance. Maximum efficiency of 44.5 percent at 100 watts and 45.7 percent at 70 watts have been obtained which is an improvement of less than one percentage point over the results reported at the end of last quarter. Even though the efficiency is about the same, an understanding of the effects of peak magnetic field and magnet period have been obtained.

Figure 1 shows a standard plot of power output, saturation gain and beam efficiency vs. helix voltage. It shows that it is necessary to have a peak magnetic field of at least 850 to 900 gauss to realize the beam efficiency of 35.9 percent. The effect of the higher value of field is to shift the optimum helix voltage upward about 50 to 60 volts. This probably results from the slightly smaller equilibrium beam diameter caused by the higher field. The higher field has other effects which do not show on this plot. They will be discussed later in conjunction with other figures.

Another design aspect which has never been evaluated is the effect of the magnetic field period on the RF defocusing of the electron beam in the large signal region of the tube and also its effect on efficiency and gain performance.

Tubes with Serial Numbers 3 through 6 have been constructed with short period magnets over the large signal section at the output end of the tube and longer period magnets over the balance of the small signal section of the tube. On the initial tests of Tube No. 6, the last 2.0 inches of the magnet stack used a magnet period of .312 inches. The rest of the length of the tube uses a magnet period of 0.370 inches. In order to obtain the required magnetic field in the short period section, it has been necessary to use platinum-cobalt magnets in the odd numbered cells counted from the output end. The shorter period was used to guarantee good focusing of the electron beam through the large signal section of the helix, but no experiment has been carried out to verify if it is indeed necessary. It would be desirable from a cost standpoint as well as from the standpoint of standardization of parts to use the longer period Alnico 8 magnets over the entire length of the tube.

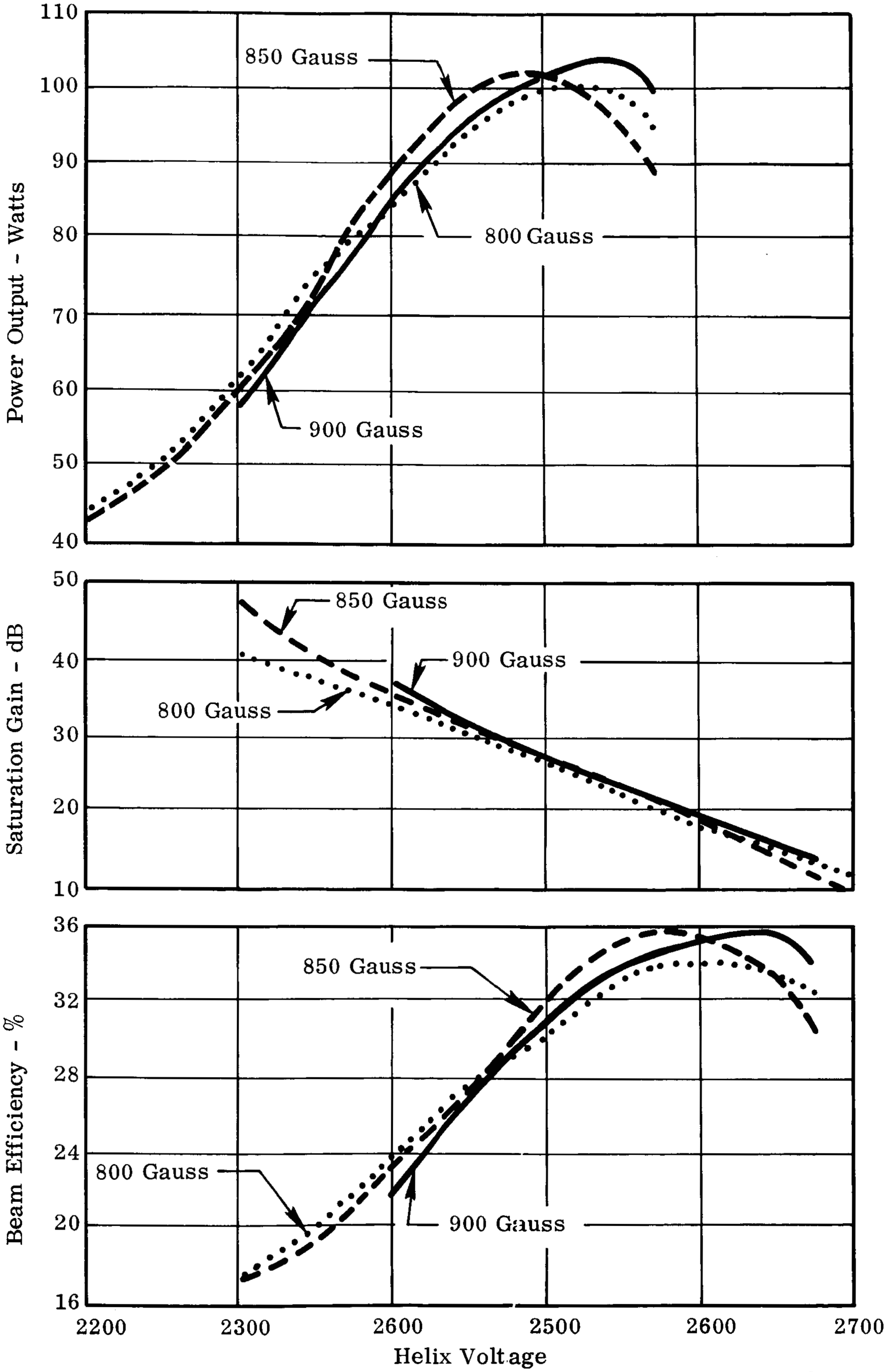

Fig. 1 - Comparison of power output saturation gain and beam efficiency at three values of peak magnetic field for the short period field on WJ-395 No. 6 at 2.3 GHz.

Tube No. 6 was constructed so that an experiment could be performed whereby the two different periods of magnets could be used over the large signal section on the same tube. This was accomplished by constructing the pole pieces so that they were tight fitting but free to slide on the body of the tube. This allowed a series of experiments to be run with the shorter period at the output end and then another series with the longer period at the output and the shorter period moved up into the small signal section where it was known that period would have no effect on focusing. This is shown in schematic form in Fig. 2. A careful set of tests were made under both conditions with power, saturation gain, beam efficiency, depressed efficiency being measured vs. helix voltage and frequency. Input-output curves were also measured.

Figure 3 shows power output, saturation gain and depressed efficiency vs. frequency for two different magnetic field values for the short period and one field value for the long period. Comparing the curves at the 850 gauss level, it is seen that the long period tends to hold up efficiency over a wider frequency range although it does not change the bandcenter value of efficiency.

The long period magnets produce lower gain by about three dB under equivalent efficiency conditions. The gain is lower even when corrected for the difference in helix voltage. Under normal conditions, the lower gain would be expected to affect the efficiency performance, but in this case it appears that it does not.

Figure 4 is a comparison of saturation gain and beam efficiency vs. helix voltage for the two different periods. The characteristics seem to differ very little at the two periods with maximum beam efficiency values in each case being within 1/2 percent of one another. Even when the different optimum helix voltages are considered there seems to be less gain difference between the two conditions than that shown in Fig. 3.

Figure 5 shows the depressed efficiency and helix current as a function of collector voltage. No more than 1/2 percent difference in depressed efficiency can be seen for the two different periods under full depression. Helix current is within 0.5 mA. It is interesting to note that even though the 900 gauss field leads to a higher helix current interception when helix and collector are at the same voltage, at maximum efficiency the 900 gauss field leads to lower helix current interception under full depression.

Figure 6 shows the input-output curves for two different values of magnetic field at the long period. A comparison between two different periods at the same magnetic

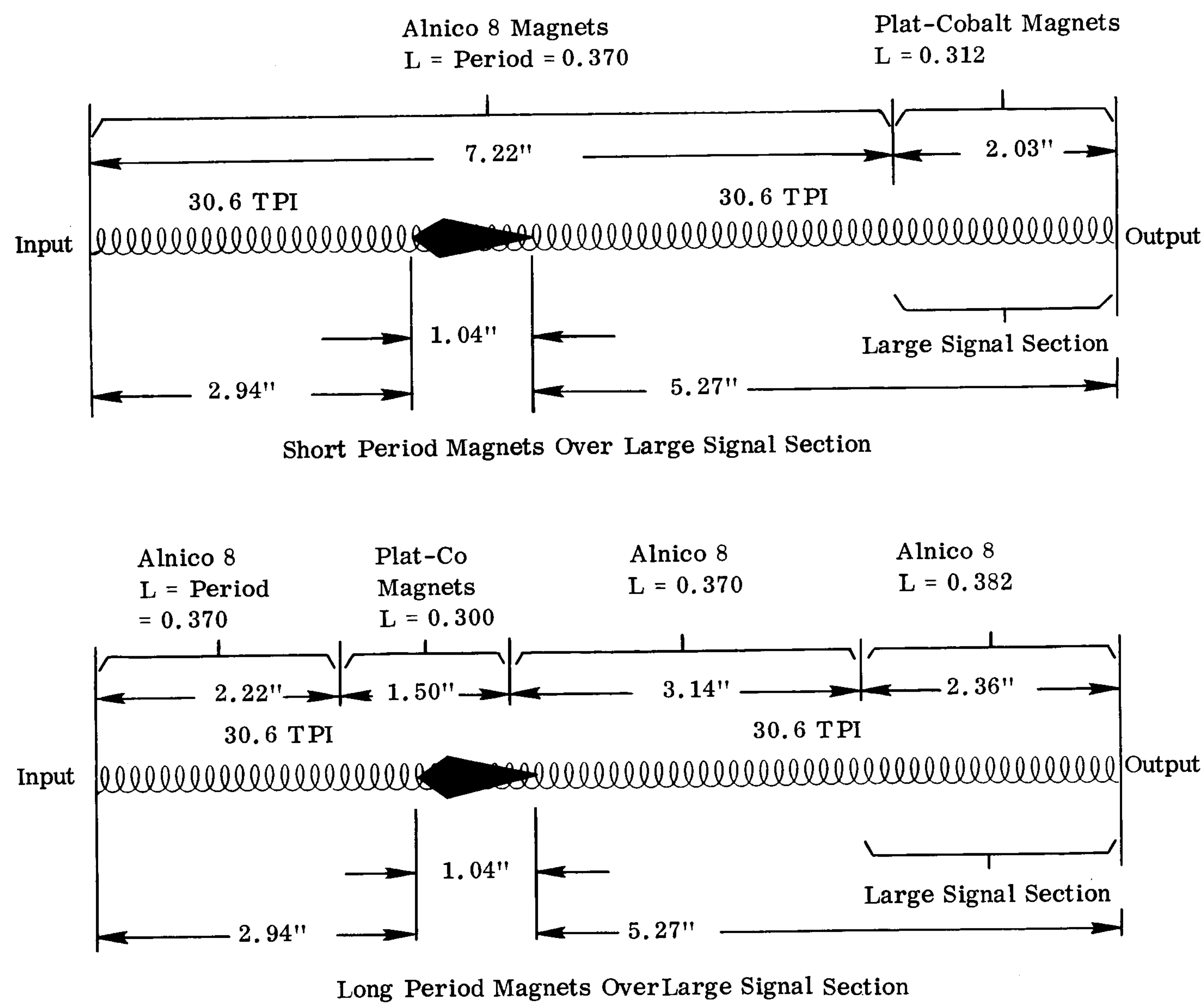

Fig. 2 - Magnet period configuration for short and long magnet period tests over large signal section of WJ-395 No. 6.

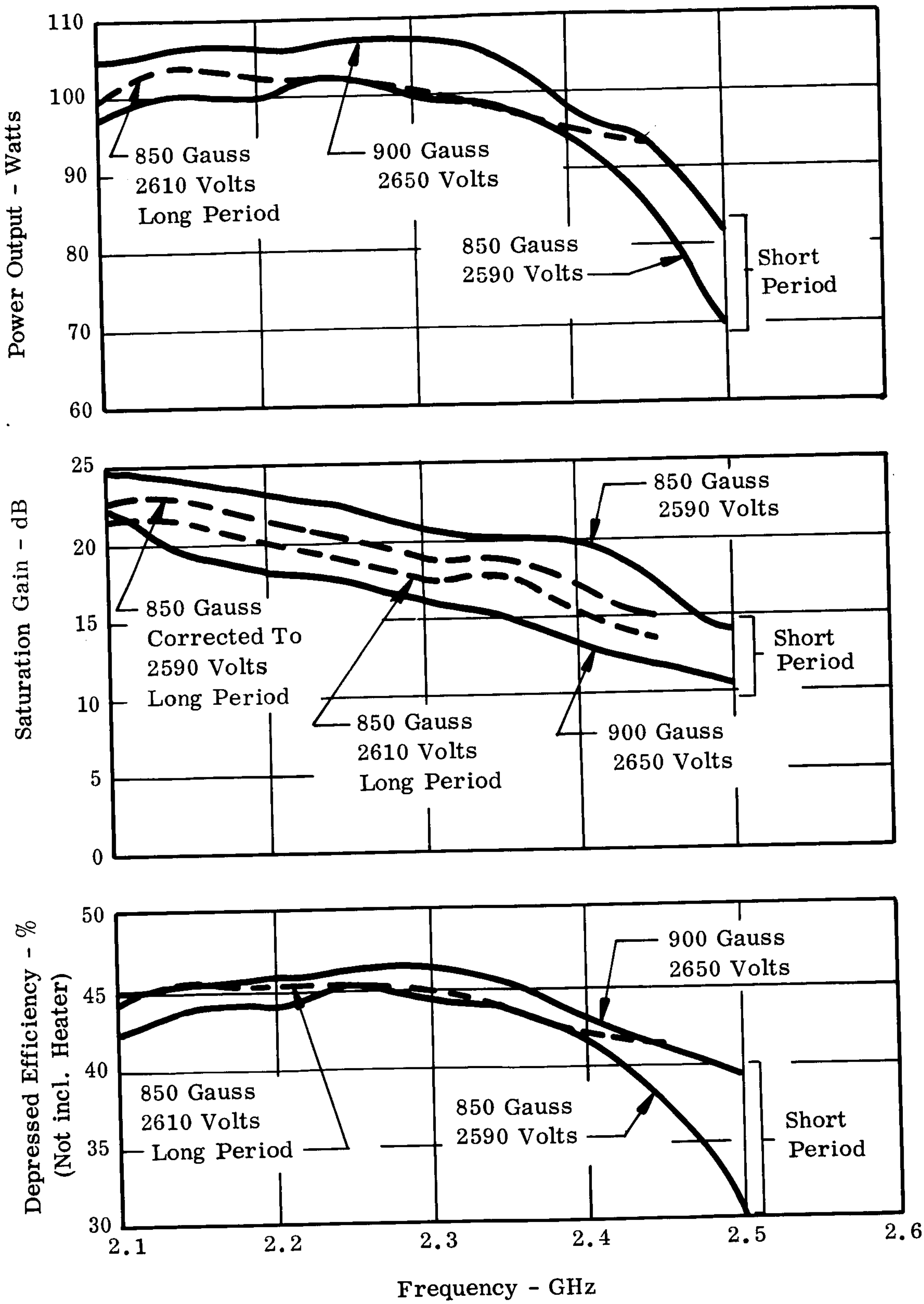

Fig. 3 - Comparison of performance on WJ-395 No. 6 with long and short period magnets over large signal section of tube. Beam current = 110 mA.

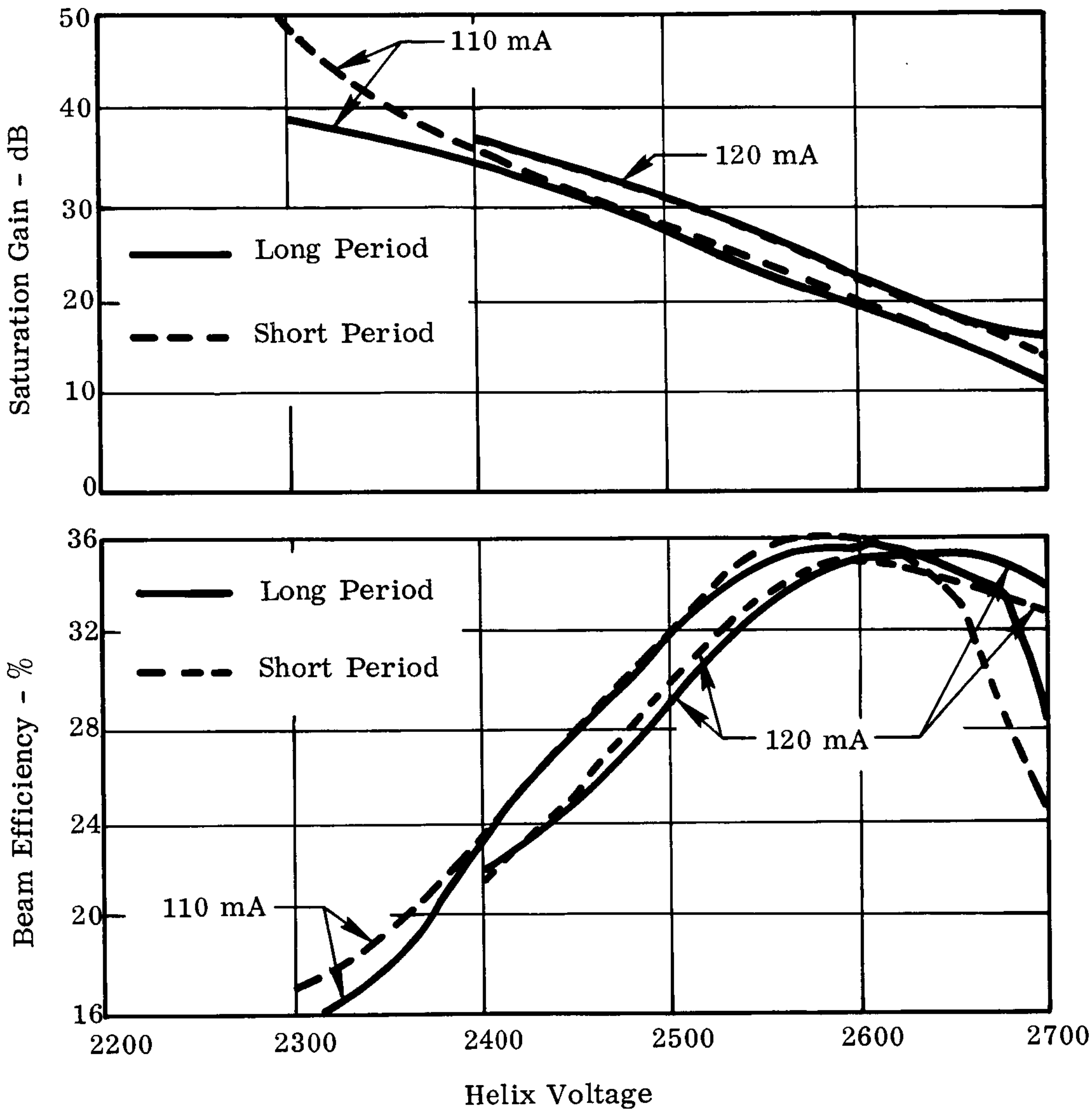

Fig. 4 - Comparison of saturation gain and beam efficiency of WJ-395 No. 6 for long and short period magnets over the large signal section at 2.3 GHz. Peak magnetic field = 850 gauss. Beam current = 110 and 120 mA.

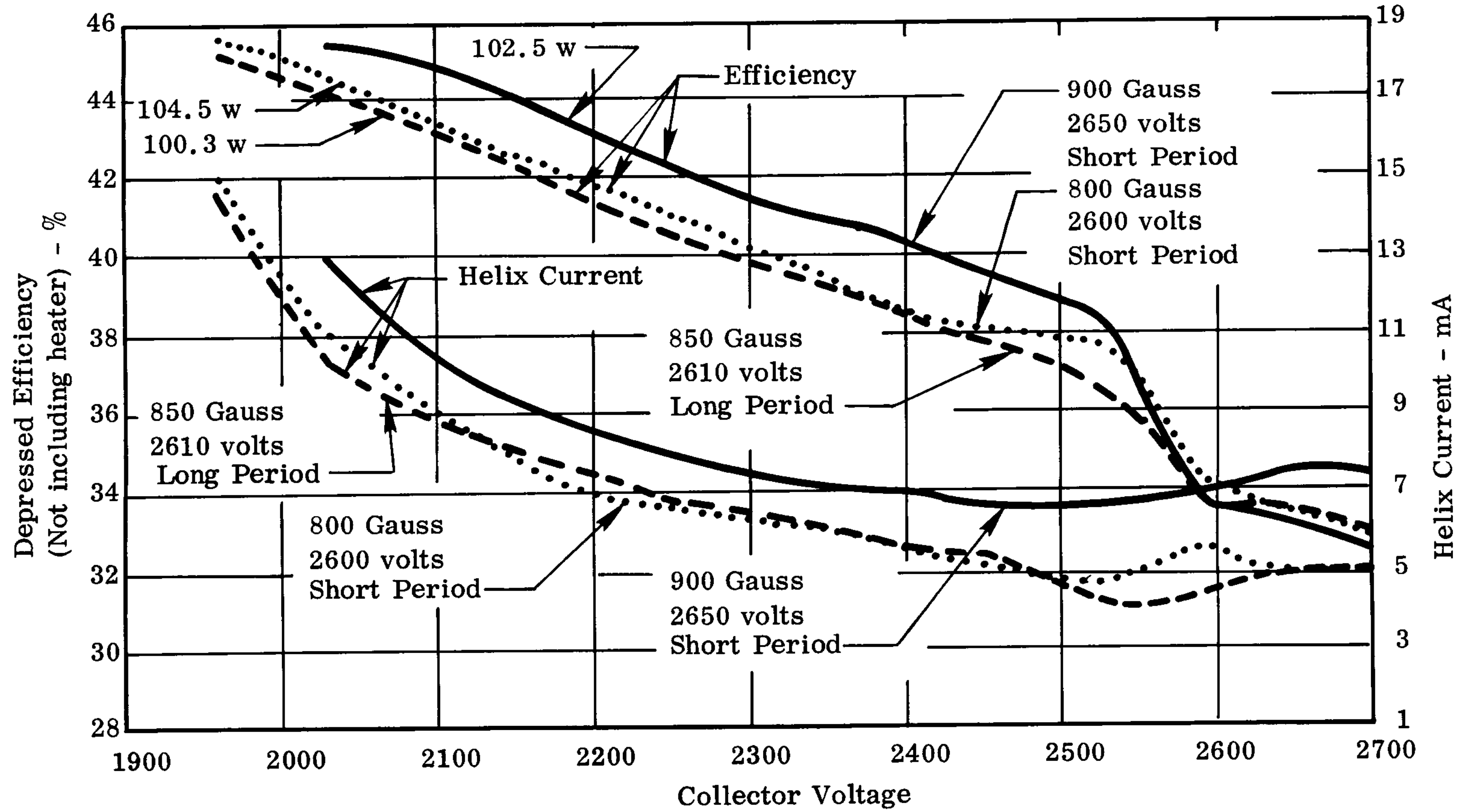

Fig. 5 - Comparison of collector depression characteristics of WJ-395 No. 6 for long and short period magnets over large signal region. Frequency = 2.3 GHz. Beam current = 110 mA.

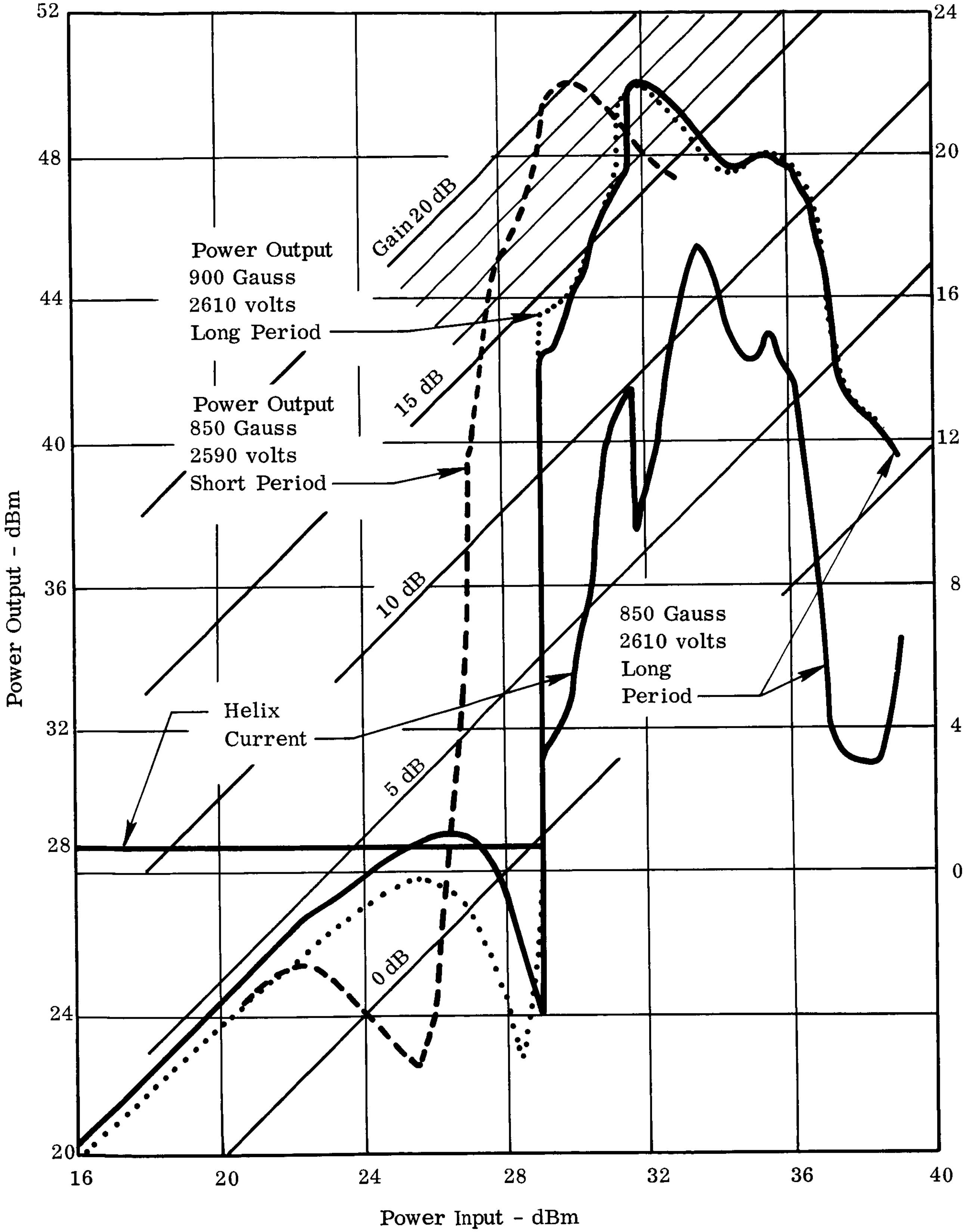

Fig. 6 - Transfer curves of WJ-395 No. 6 with long and short period magnets over large signal region. Beam current = 110 mA. Frequency = 2.3 GHz.

field is also shown. It shows that the effect of field change is essentially negligible in the saturation region. The change in period causes the voltage for maximum efficiency to change by about 20 volts. The efficiency value remains the same and the major effect is a change in gain. This change in gain is almost exactly what would be expected for a 20 volt change in helix voltage, i.e., at 8 dB/100 volts (see Fig. 4) a 1.6 dB change would be expected and a 2 dB change is observed. The helix current goes through interesting variations as a function of drive. It appears to exhibit a peak and then a minimum just before saturation. There are rapid changes in current at the drive levels corresponding to sudden changes in power output. These rapid rises in power output are stable and repeatable conditions within the tube. They do not represent conditions of start or stop oscillations. According to large signal computer calculations for large overvoltage situations, these sudden changes in power output are due to rapid reversing of phase of the fundamental component of the beam current.

Conclusions on the Effect of Magnet Period

From the observed effects of changing the period of the magnetic field in the large signal section of the tube, it can be concluded that uniform period, Alnico 8 magnets can be used over the entire length of the tube.

WJ-395 S/N 7

The design of this tube uses a uniform helix of the same design as Tube No. 6 except that the output section of the helix was intended to be 1.0 inch longer. When it was later dismantled, it was discovered that the spray mask for the attenuator must have been reversed when the rods were sprayed which placed the long output taper towards the input of the tube. This made output section of the helix following the attenuator approximately 0.5 inches longer than originally planned. This additional length is reflected in the dimensions shown in Fig. 7. It was intended that the additional physical length of the output section would explore a change similar to that used between Tube Nos. 2 and 3 of the company sponsored research program.

Performance of the tube was below expectations. The standard characteristics of power output, saturation gain and beam efficiency are plotted in Fig. 8 along with a curve of Tube No. 6. It is seen that efficiency of No. 7 is well below that of Tube No. 6. This is not the type of performance change that would be expected for an increase in helix length and certainly was not observed on the company sponsored tubes. The effect of the longer helix should be to move the helix voltage for maximum efficiency to lower values of perveance. Data were measured at three frequencies to make certain that the characteristics were optimum at 2.3 GHz.

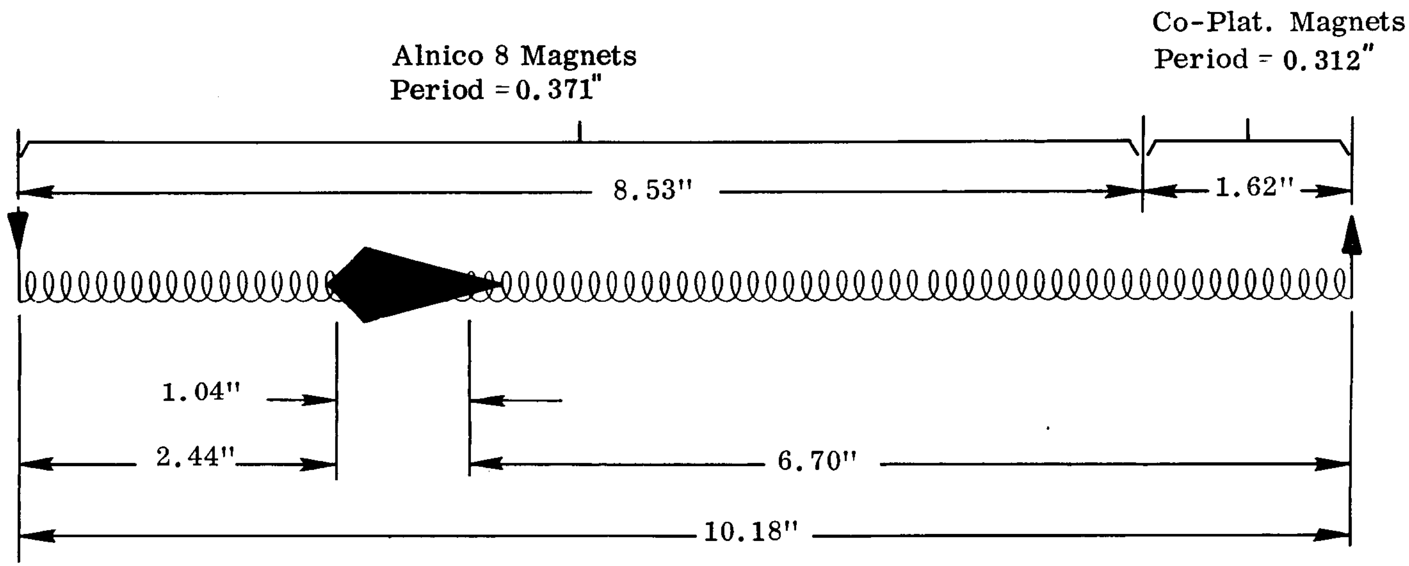

Fig. 7 - Magnet and helix design of WJ-395 No. 7

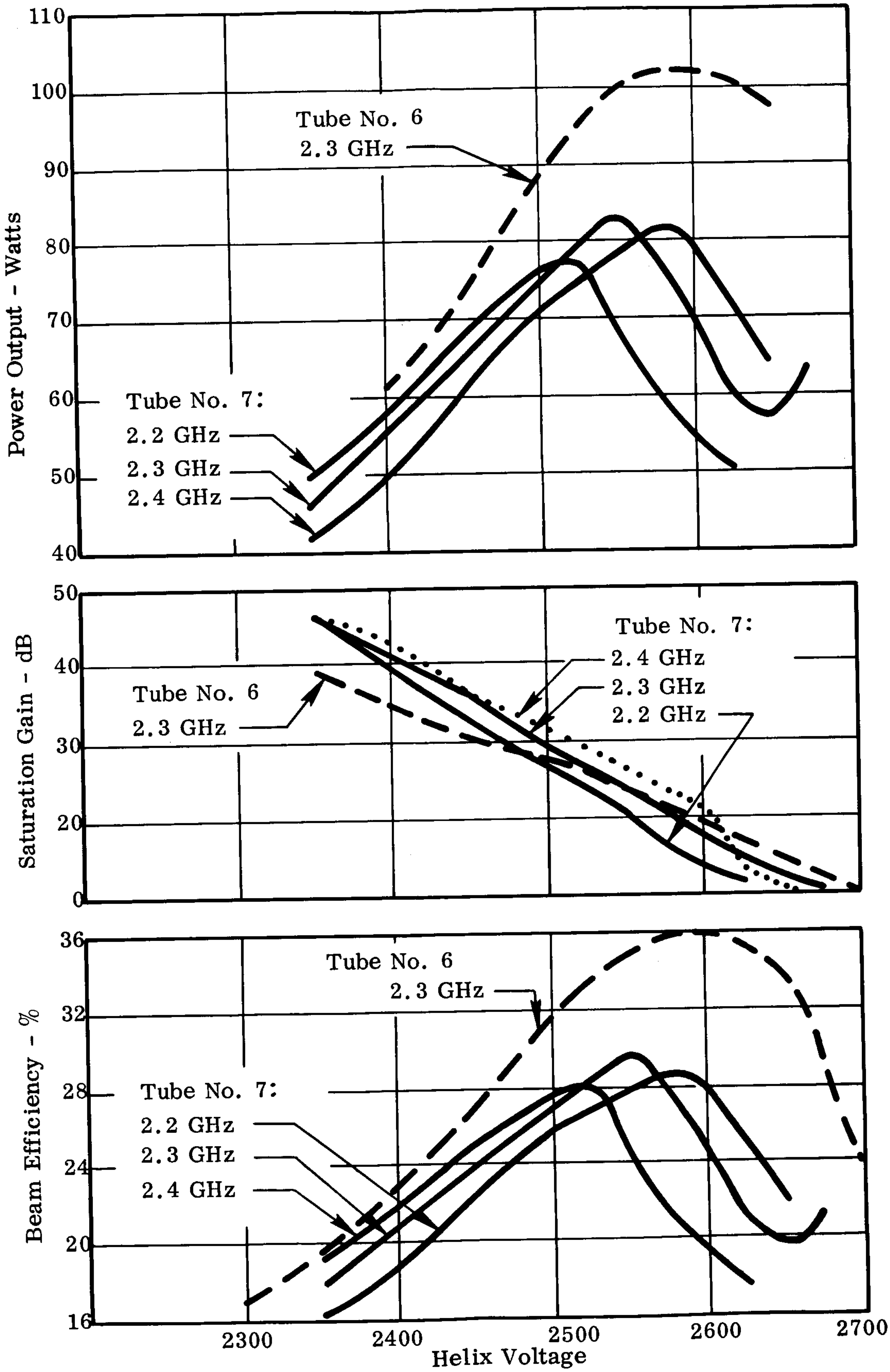

Fig. 8 - Comparison of performance of WJ-395 No. 7 with WJ-395 No. 6 at a beam current of 110 mA and a peak magnetic field of 850 gauss.

Comparing the saturation gain of the two tubes at 2.3 GHz as a function of helix voltage, Tube No. 7 shows more gain at the lower voltages because of its longer output helix section but has a steeper slope vs. voltage which is also due to its length. The two curves essentially cross at 2550 volts and should have the same efficiency at this point based upon observed performance on the company sponsored tubes. Since beam efficiency is low by 6 percentage points, it must be concluded that another factor is affecting efficiency. This must be helix loss.

Figures 9 and 10 show the performance of Tube No. 7 at 81 and 120 mA respectively at the three frequencies. These data were taken to determine that the efficiency did not optimize at some other beam current than 100 mA.

Figure 11 shows a plot of the input-output curves for Tube Nos. 6 and 7. They are operated at the same beam current, but helix voltage was chosen to give maximum efficiency in each case. It is seen that small signal gain is lower for No. 7 despite the fact that it has a longer output helix and is operating at a lower voltage. Both factors should give higher small signal gain. This again points toward helix loss as the factor leading to reduced efficiency performance.

Note also in Fig. 11 the more abrupt rise of power output with the longer helix. This is typical of greater output helix length under high overvoltage conditions.

It will be important, on future models, to widen out the high efficiency region of this curve. This can be accomplished through the use of a positive taper section at the output end of the helix. This will tend to bring the small signal gain to higher values. Although this in itself is unimportant to the saturation performance, it gives a better transition from small signal to large signal operation and broadens the saturation region by lifting the leading edge of the peak.

Before dismantling of the tube for examination, it was x-rayed to determine if the helix exhibited a uniform pitch. No observable non-uniformities can be seen on the radiograph. The helix was then removed. It was, of necessity, destroyed by the removal process. The helix support rods were carefully examined and two facts were discovered. (1) A considerable deposit of metal was on the inside surface of the rods between helix turns over the last one inch section. This is most likely metal rubbed off from the helix insertion mandrel at the time that the helix was triangulated into the barrel. This is most likely stainless steel. Tests will be performed to determine if possible what this material really is. The second fact showed that the effective position of the attenuator was farther towards the input of the tube than the design position. It was determined that this probably occurred from an accidental

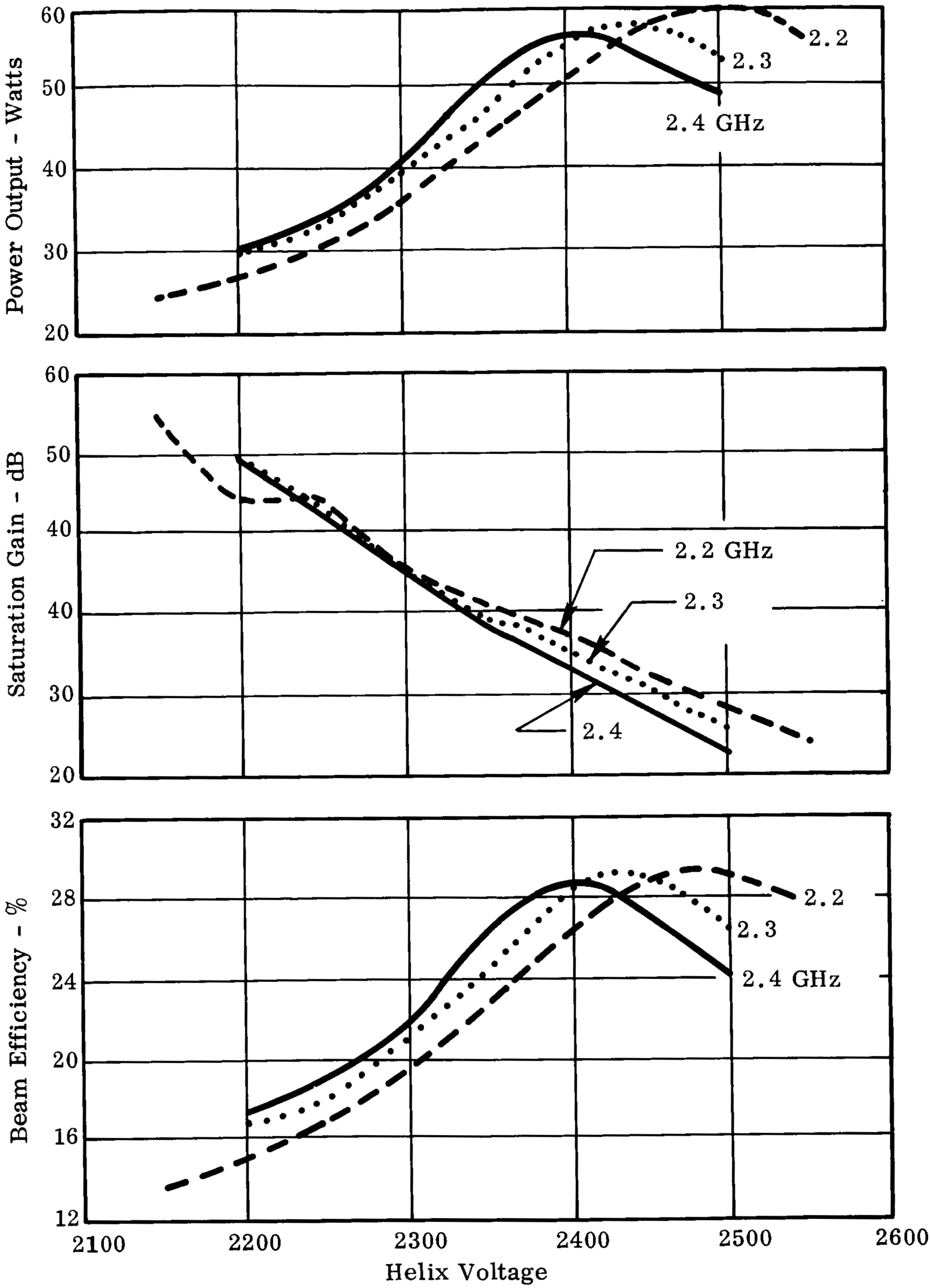

Fig. 9 - Performance of WJ-395 No. 7 at a beam current of 81 mA and a peak magnetic field of 850 gauss.

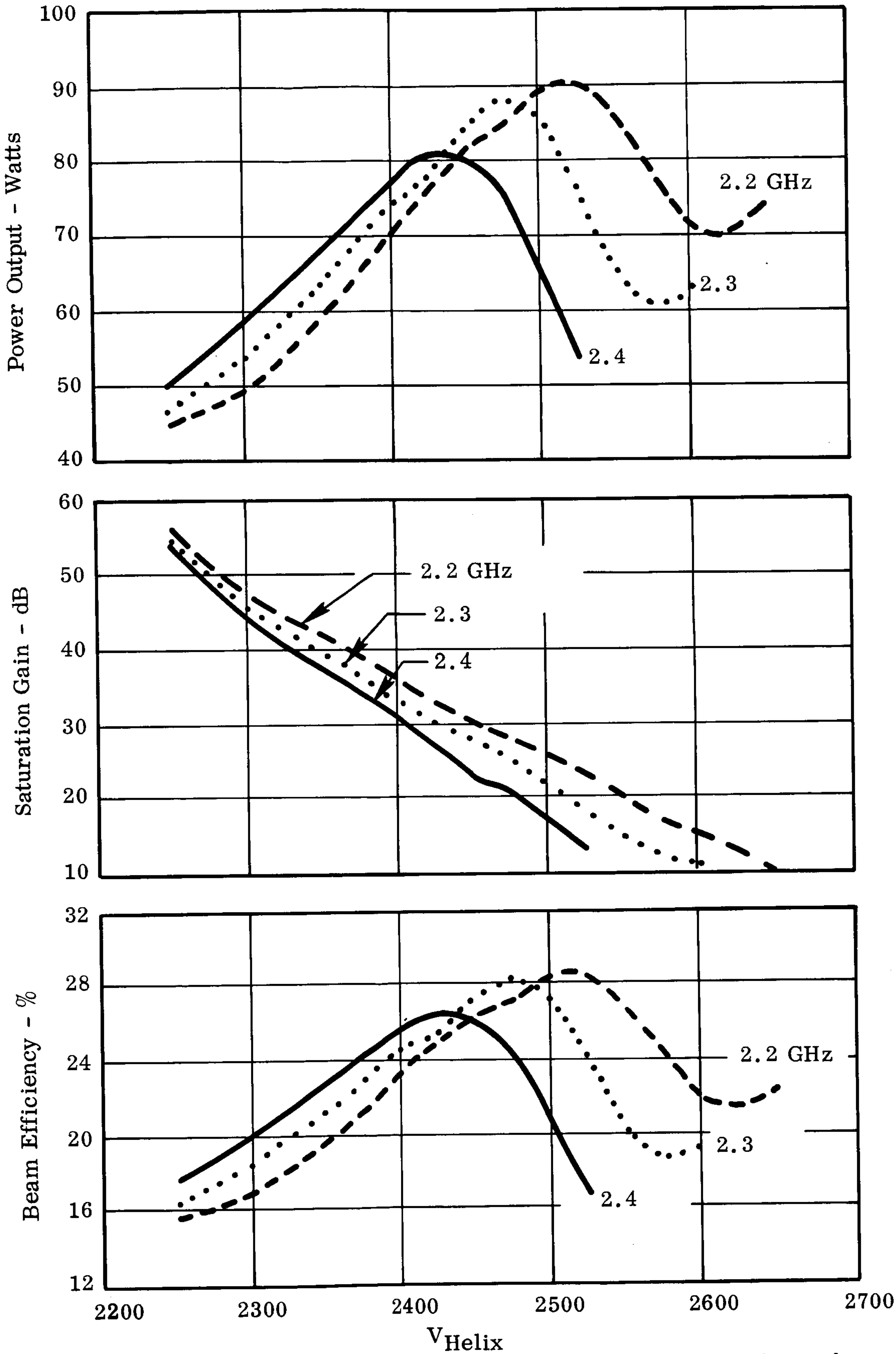

Fig. 10 - Performance of WJ-395 No. 7 at a beam current of 120 mA and a peak magnetic field of 850 gauss.

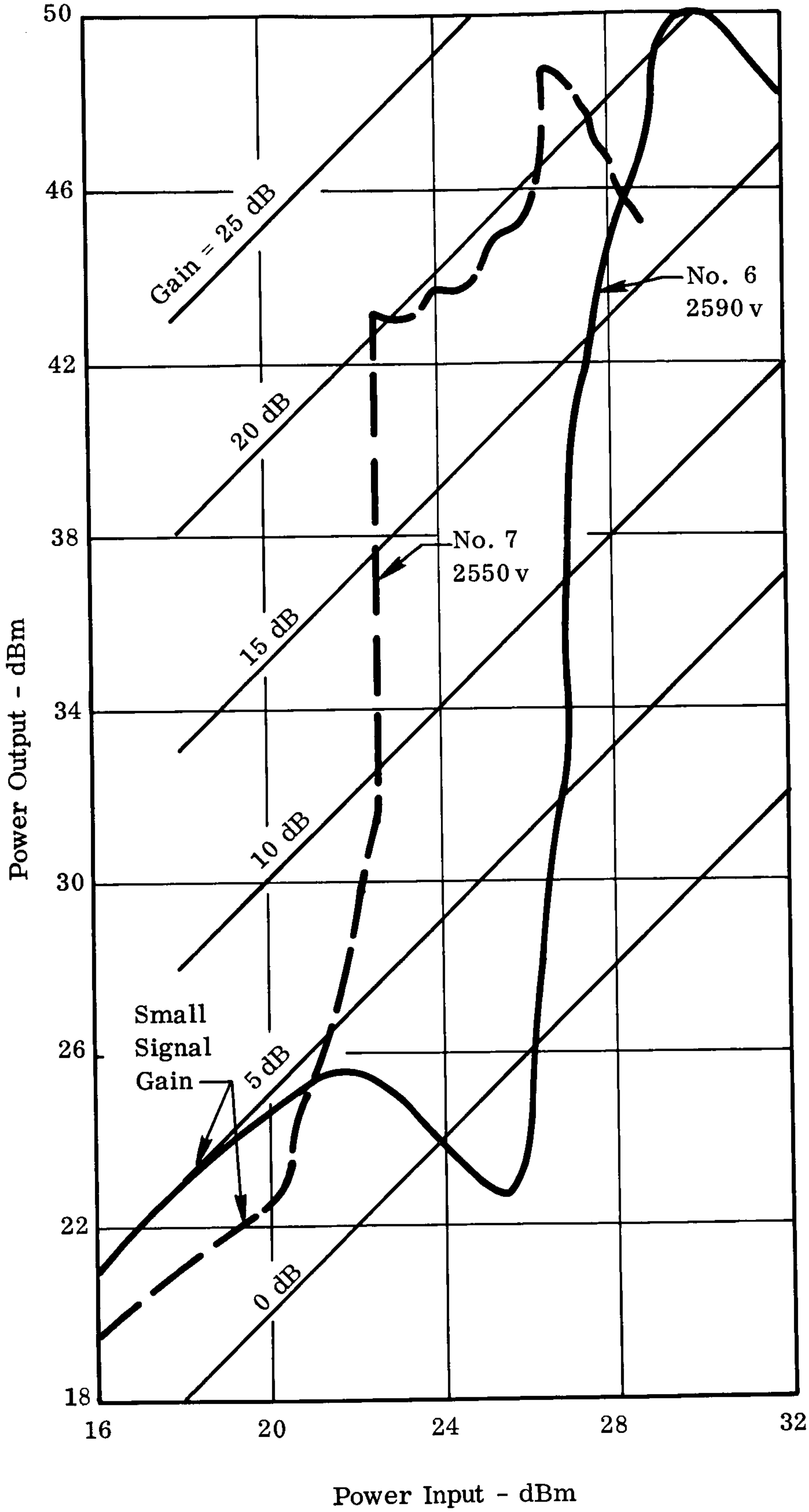

Fig. 11 - Comparison of transfer curves of WJ-395 No. 6 and No. 7 at maximum efficiency. Beam current = 110 mA. Frequency = 2.3 GHz. Peak magnetic field = 850 gauss.

reversal of the spray mask at the time that the rods were sprayed with attenuation material. The output helix section was approximately 0.5 inch longer than the design called for. It is not felt that this latter fact would cause the efficiency discrepancy observed.

Conclusions on Tube No. 7

Tube No. 7 is an anomaly. Its performance did not correspond to that which would be expected from that helix design. Electrical performance and material found on the helix rods after dismantling both tend to indicate that excessive helix loss existed and was the major factor leading to the loss in efficiency.

III. PROGRAM FOR THE NEXT QUARTER

Positive taper tubes will be built. They will explore the effects on efficiency and broadening of the saturation region of this type of helix change.

Work will be done to encapsulate Tube No. 6 and temperature and vacuum tests will be performed to determine if the design is satisfactory under these conditions.