HIGH EFFICIENCY KLYSTRON FOR THE SPS APPLICATION

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INTRODUCTION

Proposed satellite power stations, where solar energy is to be converted to microwave energy and beamed to earth to be converted to ac power, will require large numbers of high efficiency microwave devices. A total microwave tube operating efficiency of 85% has often been mentioned as the minimum acceptable. It has been estimated that one percentage point in tube efficiency is roughly equivalent to two hundred million dollars in installation costs for a single satellite power station.

During the past several years interest has centered on the klystron as a possible source of microwave energy in the satellite power station because of high power output (50 to 70 kW), high gain (40 to 50 dB), low noise (-181 dB/Hz or greater) referenced to the carrier, ease of phase control, and potential for very long life. While the state-of-the-art operating efficiency of the klystron is lower than that of the crossed field tube, it may be possible to enhance klystron efficiency through the use of collector depression, that is by recovering energy from the spent electron beam after microwave amplification.

Any study of the SPS klystron at Varian starts with the VKS-7773 experimental 50 kW S-band tube tested at 74.4% base efficiency.[1] This tube was the culmination of efficiency studies covering klystron electron beam microperveances in the range of 1.0 to 0.5 micropervs. The lower value was used in this high efficiency klystron. Design considerations for the SPS klystron use the VKS-7773 as a design bench mark. Theoretical studies indicate likely modifications that should yield some increase in klystron base efficiency. Study of the efforts of a number of workers in the field of depressed collectors, moreover, suggests that the recovery of energy still present on the electron beam after microwave amplification may lead to a total efficiency of close to 85%.

This paper discusses these matters and others in some detail. Subjects considered include efficiency, noise, harmonics, cooling, and life. The mod-anode, to be employed for beam control, and the depressed collector, used in spent electron beam energy recovery, are described.

THE VKS-7773 KLYSTRON

The VKS-7773 experimental klystron cw amplifier was tested at 50 kW power output and 74.4% tube base efficiency when operated at 28 kV and 2.4

amperes beam current in the 1970 tests described by Erling Lien of Varian.[1]
Figure 1 is a photograph of the klystron. The tube used a 0.5 microperv
electron gun (bottom of picture), seven resonant cavities (within the 14"
length between magnetic polepieces), and a standard water-cooled collector
(top of picture). The resonant cavity structure employed two second
harmonic cavities. These contributed to the electron beam bunching process
and high electronic efficiency. They also permitted use of a relatively
short resonant cavity system. The klystron was tunable within the frequency
range 2425-2475 MHz. A waveguide output and standard pillbox rf output
window were employed. Separate water cooling systems were used on the
klystron body, output cavity, and collector to permit analysis of power
dissipation throughout the klystron. RF power output was determined through
this power analysis, combined with beam power, calibrated coupler, and
calorimetric water load measurements.

Figure 2 shows the power output and base efficiency observed with the
VKS-7773 CW klystron as a function of beam voltage. Over the beam voltage
range from 20 to 28 kV, power output varied from 21 to 50 kW. Base
efficiency was above 70% even at the lower beam voltage, reaching 74.4% at
28 kV.

After microwave amplification, the spent beam of the VKS-7773 still has
about 14.3 kW of energy, ordinarily dissipated in the collector. If a
depressed collector were used to recover a portion of this energy, the
overall efficiency could be increased. Figure 3 shows the total klystron
efficiency as a function of collector recovery efficiency for this case. If
half of the spent beam energy were recovered, overall efficiency would be
85%.

NEW HIGH EFFICIENCY DESIGN

Table 1 shows principal operating characteristics of the VKS-7773
experimental CW klystron amplifier and those of a new design aiming at
higher operating efficiency. The VKS-7773 was designed to employ a 0.5
microperveance electron beam. This choice stemmed from computer work on
designs using 0.5 to 1.0 microperv electron beams. Theory predicts high
electronic conversion efficiency, the efficiency with which rf energy is
coupled from the electron beam into the resonant output cavity, for low
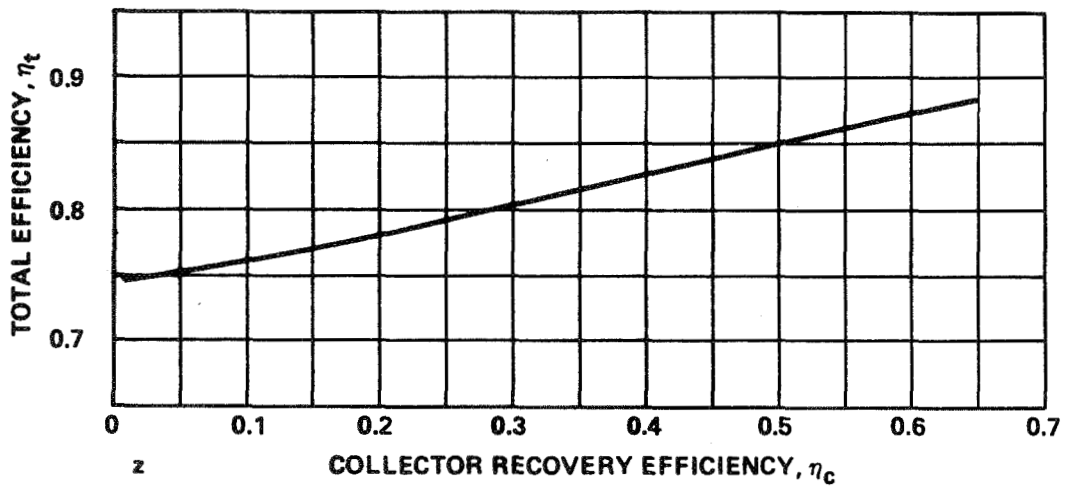electron beam microperveance. Use of a low electron beam microperveance

~14"
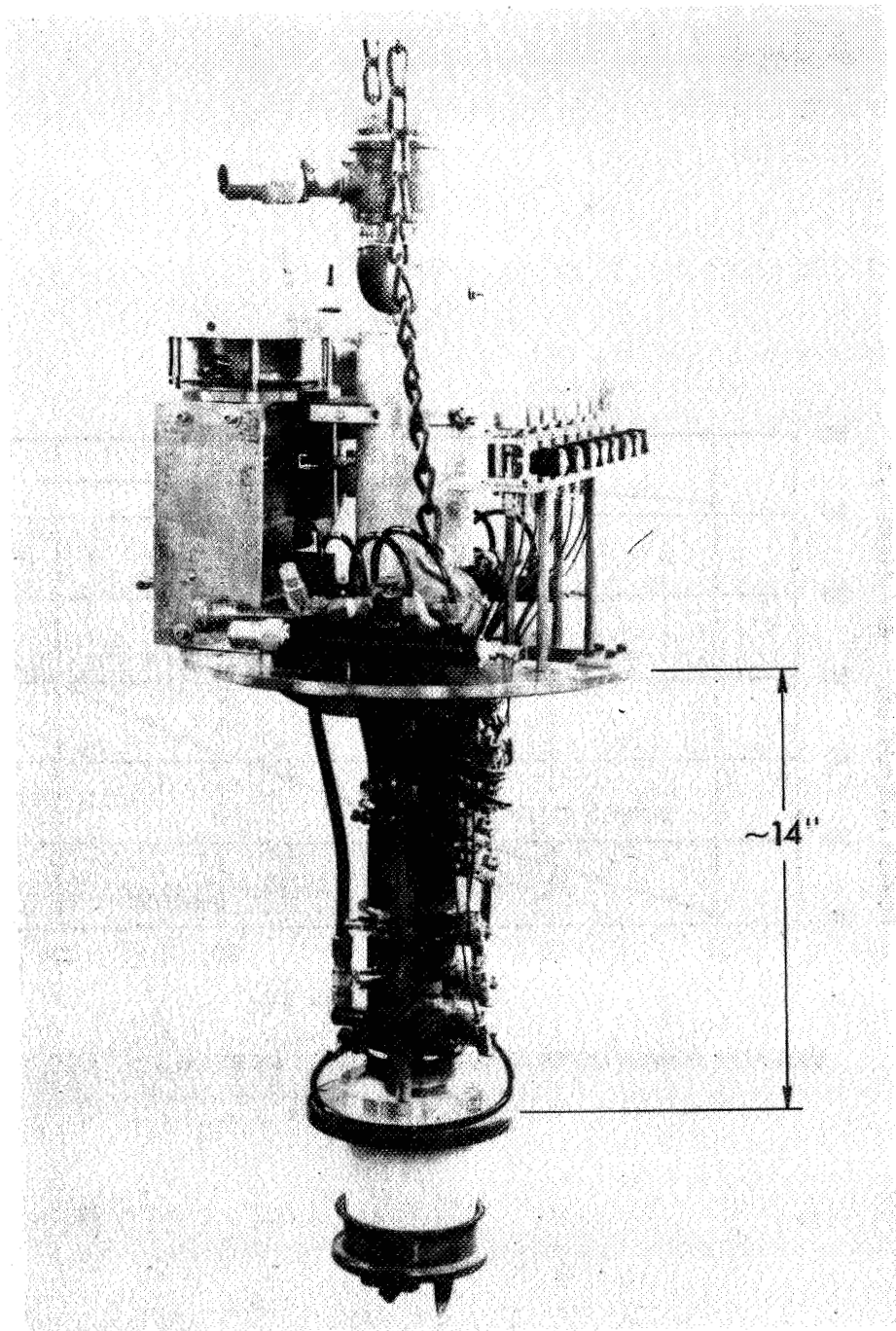
VKS-7773 EXPERIMENTAL HIGH EFFICIENCY KLYSTRON CW AMPLIFIER

FIGURE 1

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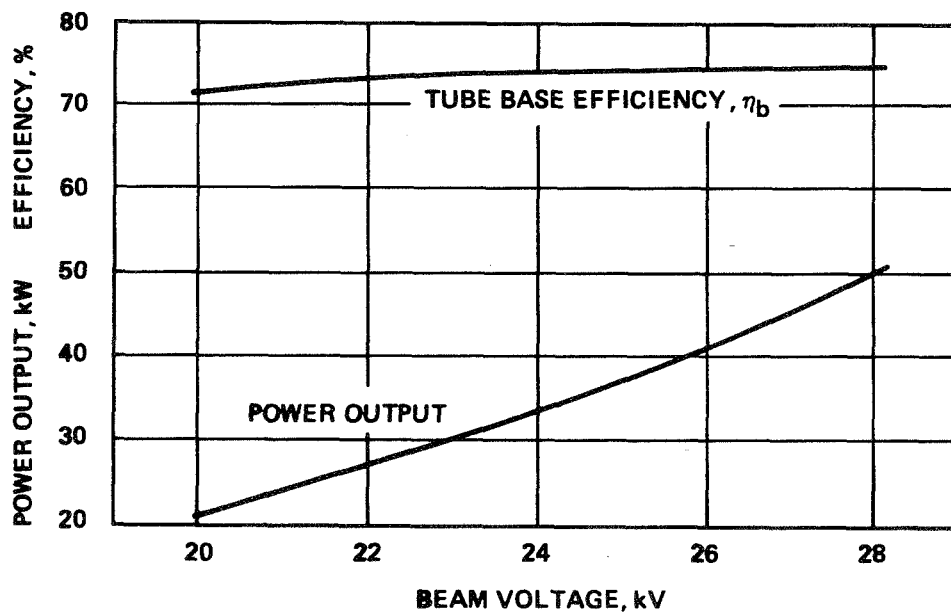
VKS-7773, POWER OUTPUT AND EFFICIENCY VS BEAM VOLTAGE

FIGURE 2

VA-7773, TOTAL EFFICIENCY WITH A DEPRESSED COLLECTOR

FIGURE 3

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means employment of a high voltage and low current beam, or a high impedance beam. For the SPS klystron, interest has centered primarily on 50 kW power output designs having electron beam microperveances in the range of 0.2 to 0.35 micropervs. Considerable study has also been applied a 70 kW power output klystron, some thoughts to a 300 kW tube. The example of the table is a 52 kW power output klystron using a 0.3 microperveance electron beam. Extrapolation of computer data leading to the VKS-7773 klystron design and study of a report on the evaluation of rf output energy extraction by Kosmahl and Albers[2] indicates an electronic conversion efficiency between 0.77 and 0.82 for this case. If one assumes a value of 0.79 and applies a 0.98 circuit efficiency, the efficiency with which rf energy is coupled from the output cavity to the useful load, then the tube base operating efficiency, product of the two, is 0.77.

Table 1

Klystron CW Amplifier Operating Characteristics

|	VKS-7773	New Design
Frequency, GHz	2.45	2.45
Tuning, MHz	±25	Fixed
Beam Voltage, kV	28	35
Mod-Anode Voltage, kV	---	17
Gun μperveance	0.5	0.85
Beam μperveance	0.5	0.3
Beam Current, A	2.4	1.96
Power Output, kW	50	52
Base Efficiency, η_b, %	74	77
Collector Efficiency, η_c, %	---	51*
Total Efficiency, η_t, %	--	85*
Saturated Gain, dB	50	50
Brillouin Field, B, Gauss	465	349

*With depressed collector assembly

RF output circuit efficiency declines with reduced electron beam microperveance, and losses increase in the rf output cavity. The net efficiency benefit from the employment of a low microperveance electron beam is limited by this fact, and an optimum condition exists, evidently within the range of 0.2 to 0.35 electron beam microperveance. For the SPS klystron, this region has been studied only from a theoretical viewpoint. The necessary experimental verification has yet to be undertaken.

The operating temperature of the rf output cavity of the SPS klystron is quite important, because a high temperature will cause a decline in circuit efficiency. The effect is quite pronounced in resonant structures of moderate unloaded Q (Q_o). A structure having an unloaded Q of 2500 at $20^{\circ}C$ would experience a loss of circuit efficiency of about three percentage points when heated to $300^{\circ}C$. If the $20^{\circ}C$ unloaded Q were 8500, the loss in circuit efficiency at $300^{\circ}C$ would be less than one percentage point. These relationships are shown in Figure 4. Unloaded Q values of 7000 to 8000 should be possible in the SPS klystron rf output cavity through design techniques described in a NASA report of work by Dr. G. M. Branch[3], in which Q's of about 6500 were obtained in C-band resonant cavities.

DEPRESSED COLLECTOR

Depressed collectors have been studied by various workers over the past twenty years or more[4,5]. Depressed collector recovery efficiencies as high as 84% have been reported in relatively low power and low to moderate base efficiency microwave linear beam tubes[6]. As tube base efficiency increases, it becomes more and more difficult to realize high collector recovery efficiency, because the spent electron beam of the more efficient tube contains electrons having a wide spread of energy and of both axial and radial velocities. A large population of relatively low energy slow electrons must exist. Collector recovery efficiency in such a case may be greatly improved through use of an electron beam refocusing section between the rf output cavity and the depressed collector entrance. A NASA report describes theoretical work by Branch and Neugebauer[7] on electron beam refocusing. The refocusing section reduces the spread in electron radial velocities and preprocesses the beam for entry into the depressed collector region at suitable angles with respect to the axis so that more effective electron sorting may be achieved.
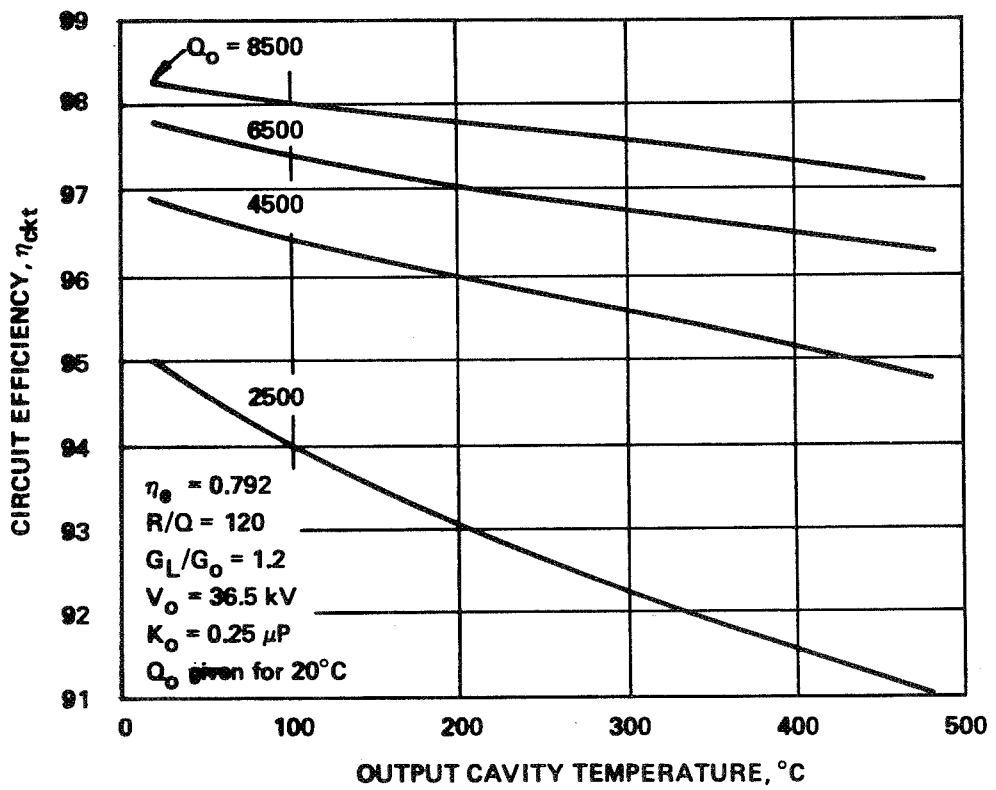
CIRCUIT EFFICIENCY VS OUTPUT CAVITY TEMPERATURE

FIGURE 4

Depressed collectors have taken various forms in the past. Probably the most successful to date is the Kosmahl design[5,6], known as the "Depressed Electrostatic Collector". Figure 5 is an example of a multistage depressed electrostatic collector. The illustration is intended only for purposes of explanation. The rf output cavity (not shown) would be on axis at the bottom of the drawing, and the spent electron beam would enter the electron beam refocusing section here and proceed upwards.

The main magnetic electron beam focusing field collapses suddenly along the axis, and all electrons in the beam experience an increase in radial velocity upon entering the refocusing section. A relatively small auxiliary magnetic focusing field is used in the refocusing section to form a magnetic "plateau". The electron beam expands, develops reduced and more nearly uniform radial velocity, and enters the main collector at angles suitable for electron sorting and collection.

Upon entering the main collector the electron beam comes within the influence of a dispersing spike at cathode potential. The beam is collected for the most part on the backs of the collecting plates, the sides away from the direction of the entering beam. The plates are biased at suitable voltages, and the collector current from each is returned to the respective power supply.

None of the details of a design for an SPS klystron depressed electrostatic collector have been worked out. Such a design will require computer analytical work and experiment. Depressed collector test models must follow design work on the basic klystron.
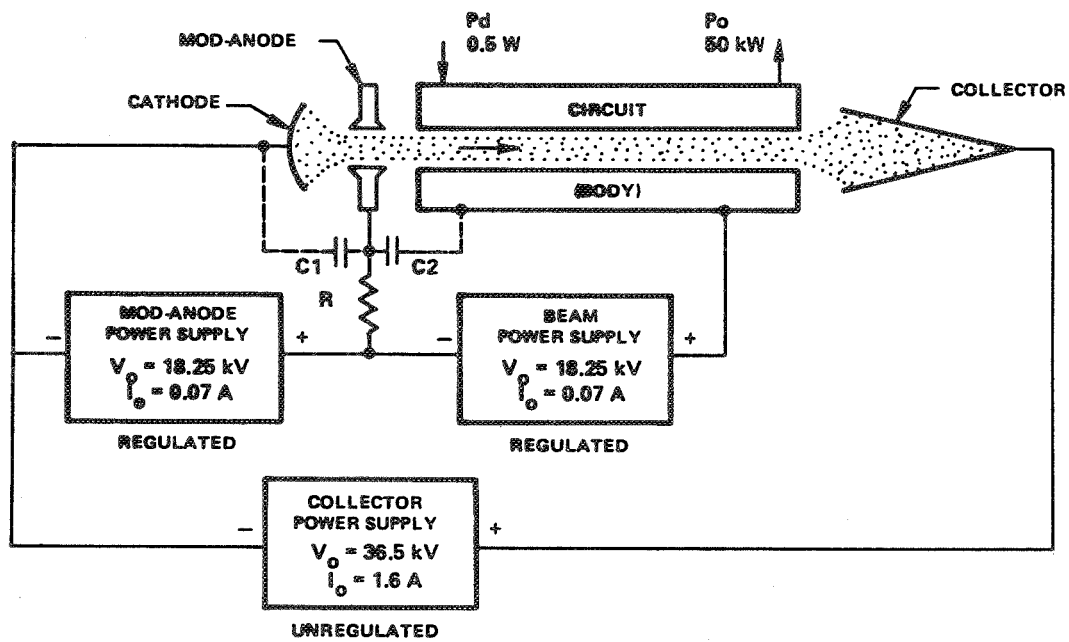
THE MOD-ANODE

The modulating anode (mod-anode) is widely used in high power klystron electron gun design. This feature offers several advantages for the SPS klystron. Figure 6 illustrates a typical mod-anode arragnement, simplified for purposes of explanation. In this case the 50 kW power output klystron employs a 0.25 microperveance electron beam operating at 36.5 kV and 1.67 amperes. The mod-anode operates at half the full beam voltage and controls the level of beam current injected into the rf circuit. Post acceleration raises the electron beam to full voltage. The mod-anode is a noninter-cepting electrode. It controls beam current without intercepting beam current. Body current in this example is 0.07 amperes. The mod-anode and

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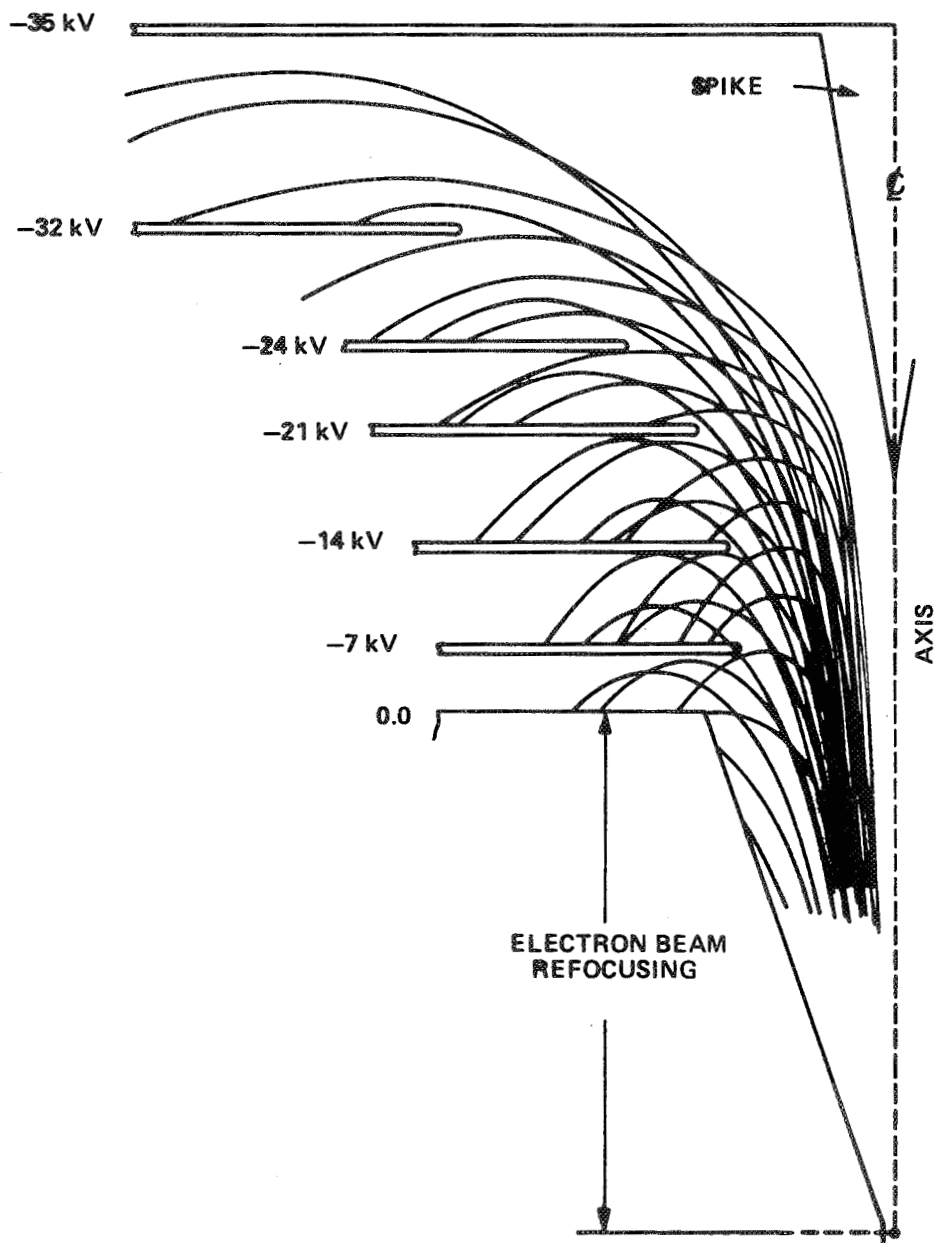
**EXAMPLE OF MULTISTAGE
DEPRESSED ELECTROSTATIC COLLECTOR**

FIGURE 5

SIMPLIFIED DIAGRAM ILLUSTRATING THE KLYSTRON MOD-ANODE

FIGURE 6

beam power supplies furnish this current. These power supplies are
well-regulated to insure good phase stability on a short term basis from
klystron input to output. The collector power supply furnishes 1.6 amperes
of beam current. This power supply need not be so well regulated.

One of the advantages of mod-anode is that the electrode divides the
total beam voltage, thereby reducing the voltage appearing between any two
adjacent electrodes. A second advantage rests in the control of beam
current, and therefore of power output. Still a third advantage relates to
occasional arcing in the cathode to mod-anode region, a possibility in any
new klystron. Since the mod-anode does not intercept electron beam current,
it may be isolated from the mod-anode and beam power supplies by a
relatively large impedance. A resistance is shown in the illustration,
though some combination of resistance and inductance may prove to be
superior with the SPS klystron. Now, should an arc occur between cathode
and mod-anode, the capacitance C1 discharges through the arc, and the fault
then quickly clears. The effect on klystron performance is a very brief
interruption of beam current and power output and prompt resumption of
normal operation in a very short time. Such occasional arcing and brief
temporary interruption of normal klystron operation is observed with many
new high power klystrons equipped with mod-anode electron guns.

ELECTROMAGNET

The use of a low microperveance electron beam means use of a high
voltage low current beam, a circumstance that tends to reduce magnetic
focusing field requirements. A major impact on electromagnet size, weight,
and power may be effected through reduction of the inside diameter to the
minimum. Figure 7 illustrates calculations made for the minimum
electromagnet ID presently viewed as possible for the new 52 kW SPS klystron
described in Table 1. The optimum design is in the region of the knee of
the curve. The circled point, for example, represents a 49 pound
electromagnet requiring 750 watts to provide an 875 Gauss magnetic field,
two and one-half times theoretical Brillouin.

The hypothetical design operates at a maximum temperature of 300°C and
includes allowance for heat pipe cooling structures. Weight of the magnetic
poles and return path is kept relatively low through use of 2V-Permandur for
this circuit. This material is an iron-vanadium-cobalt alloy having a
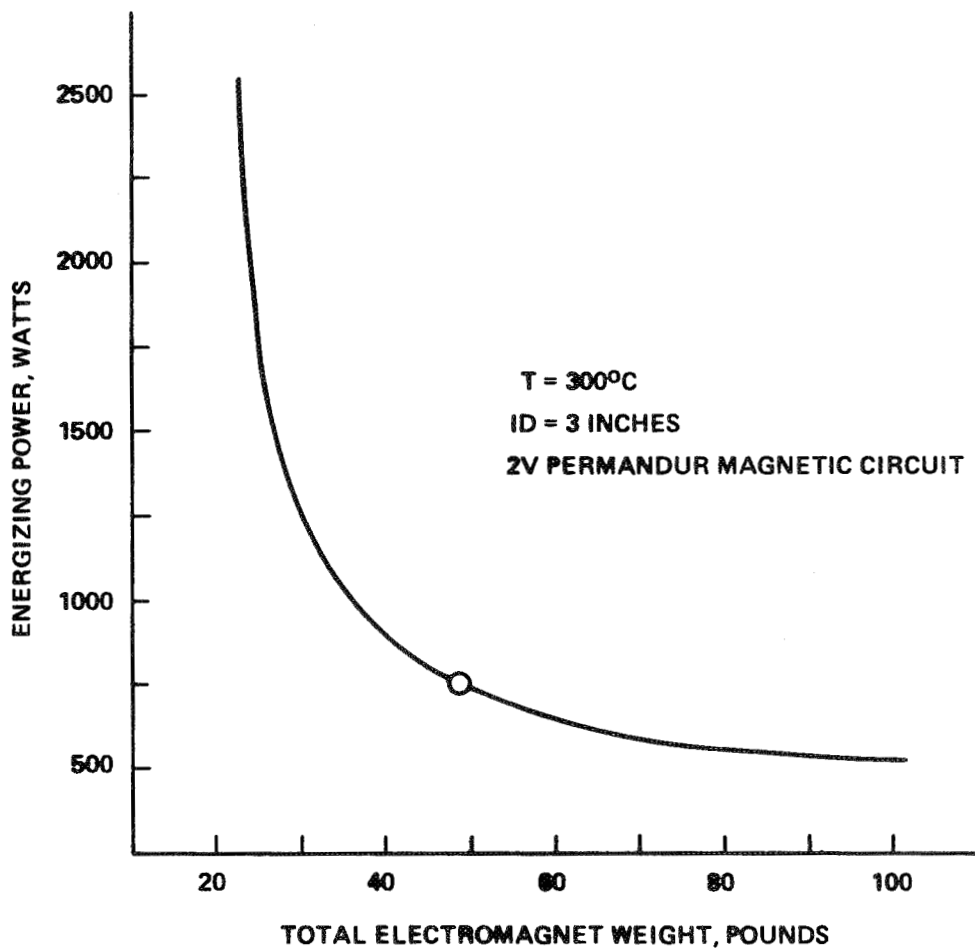
SPS KLYSTRON ELECTROMAGNET: ESTIMATED WEIGHT VS POWER TRADE-OFF

FIGURE 7

magnetic working level of 22,000 Gauss and a Curie point of 980°C. The high magnetic working level means that small magnetic cross-sections are satisfactory in the magnetic polepieces and return path. The high Curie point implies excellent magnetic stability at lower operating temperatures.

The 3 inch minimum ID of the electromagnet will require that the unit be assembled as an integral part of each klystron, at least in early sealed off versions of the tube. There is a distinct possibility that electromagnetic-derived beam focusing will be necessary only over the rf output end of the klystron, with permanent magnet focusing (using samarium-cobalt magnets) being employed with the first few cavities. Electromagnetic power and weight may be halved by this technique. The possibility should be explored during SPS klystron development.

KLYSTRON NOISE

Klystron noise power output is viewed as stemming from shot noise in the electron beam. This noise "signal" appears at the input resonant cavity interaction gap, like any rf drive signal, modulates the carrier, and is amplified by the klystron. In the SPS klystron the circuit bandwidth is quite narrow, and noise output is confined to small low level sidebands close to the carrier.

Figure 8 shows the results of a computation of klystron noise power spectral density for a 50 kW power output 50 dB gain SPS klystron. The rf drive signal is assumed to be monochromatic and free of noise. The data includes both AM and FM noise contributions expressed in dBW/Hz.

Klystron noise power output measurements are typically made relatively close to the carrier through a technique described in an IEEE MTT article by Klaus H. Sann.[8] An outstanding feature of the technique is cancellation of the carrier by means of microwave circuitry, thus permitting close to carrier noise measurements.

The SPS klystron per se will likely be very "quiet" compared to the rf drive signal applied to the klystron input. Computed klystron and amplified oscillator-driver noise powers are shown in Figure 9. A logarithmic abscissa is used better to show close-to-carrier noise. The possible noise power spectral densities for three oscillator-drivers are illustrated. The data shows only an equivalent FM noise deviation for each case. AM noise contributions are relatively much smaller.
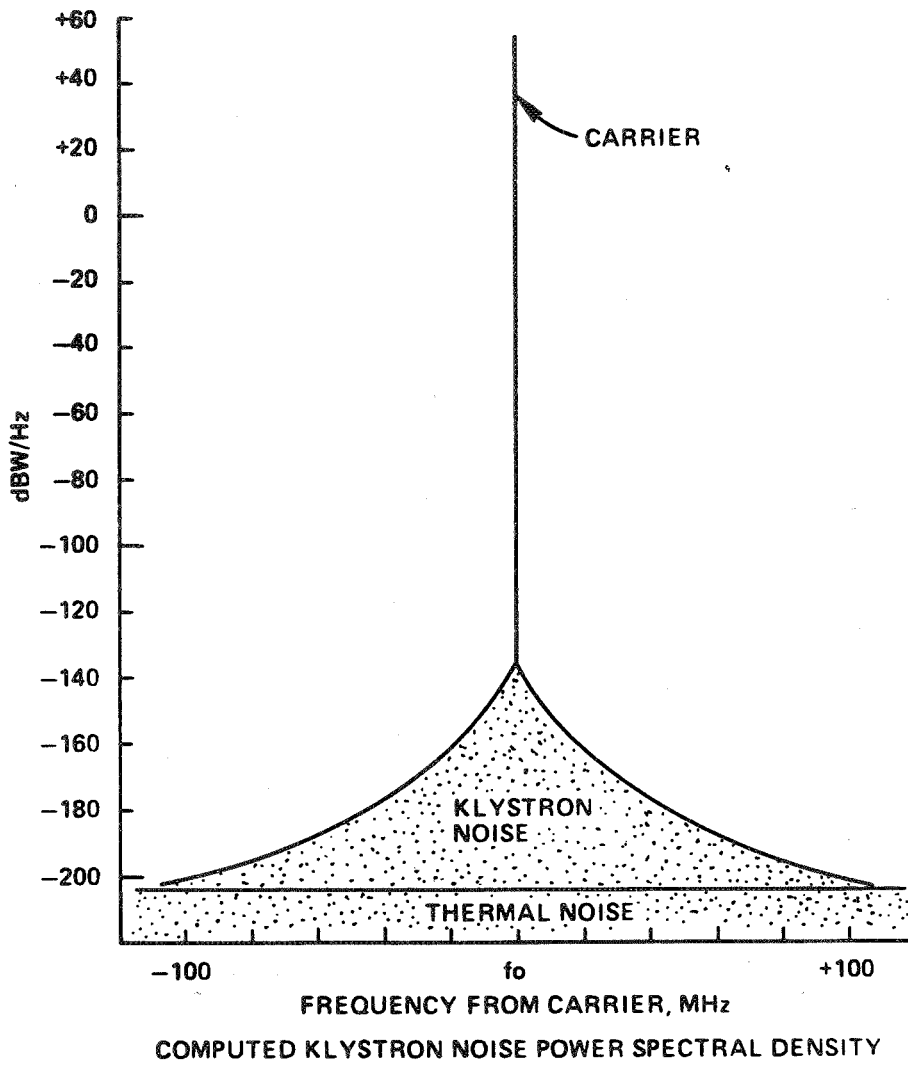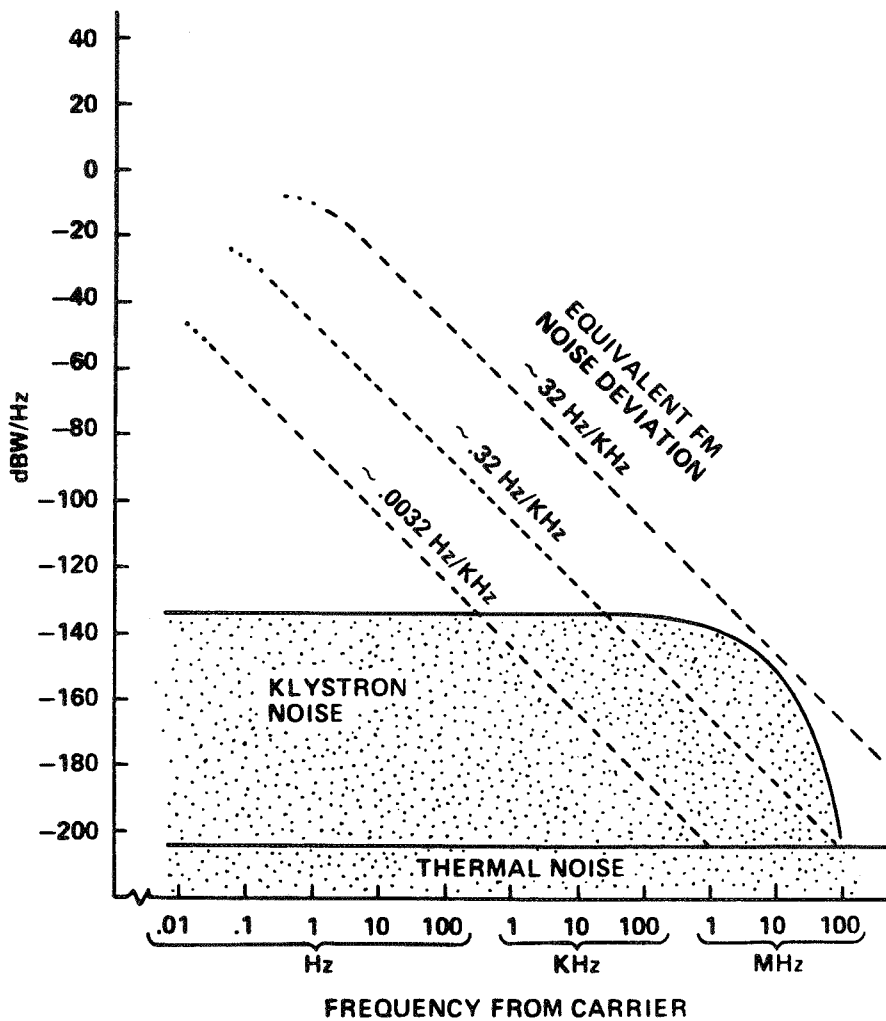
COMPUTED KLYSTRON NOISE POWER SPECTRAL DENSITY

FIGURE 8

COMPUTED NOISE POWER SPECTRAL DENSITY FOR
KLYSTRON AND FOR THREE OSCILLATOR DRIVERS

FIGURE 9

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KLYSTRON HARMONICS

The second harmonic of the SPS klystron should be close to 30 dB or more down from fundamental klystron power output. Higher order harmonics may be somewhat further down, though little experimental verification is at hand. Harmonic measurements are difficult because of the many possible modes of propagation. The subject has been studied by many workers over the years [9,10].

Klystron harmonic levels may require external attenuation in the SPS installation. Three practicable types of high power filters may be considered; the leaky wall waveguide, lossy "tee", and reactive stub array. An estimated attenuation of these filters to second through sixth harmonics is shown in Table 2. The leaky wall waveguide and reactive stub array have less and less effect as order of harmonic increases, because attenuation with these filters is active at or close to the waveguide walls. The lossy "tee", on the other hand, is more effective as order of harmonic increases, though attenuation of the lower order harmonics is less. Since the leaky wall waveguide filter is large and bulky, some combination of simpler lossy "tee" and reactive stub array seems indicated.

Table 2
Estimated Attenuation of Harmonic Filters

Harmonic	3 ft Lossy Leaky Wall	Lossy "Tee"	Reactive Stub Array
2nd	60 dB	8 dB	40 dB
3rd	40 dB	10 dB	30 dB
4th	15 dB	12 dB	20 dB
5th	10 dB	14 dB	10 dB
6th	5 dB	16 dB	5 dB

KLYSTRON COOLING

Table 3 outlines an estimate of klystron cooling requirements for the 52 kW power output klystron of Table 1. To sum up; approximately 3.5 kW of waste power from the klystron body must be dissipated at a maximum tube element temperature of $300°C$ or thereabouts; approximately 7 kW of waste

power from the collector plates may be dissipated at a maximum tube element temperature of $600^{\circ}C$ or higher.

Table 3

Estimate of Klystron Cooling Requirements

(Po = 52 kW, Ko = 0.3 µP)

Klystron Element	Power, Watts	Maximum Temperature
Heater	100	
Electromagnet	750	
RF Driver Cavities	887	
RF Output Cavity	1758	
Subtotal	3495	$< 300^{\circ}C$
Collector Plates	6938	$> 600^{\circ}C$
Total	10433	

The collector plates in this case are designed to handle only the waste power remaining in the spent electron beam after microwave amplification. With loss of rf drive power, the electron beam must be turned off at once. The mod-anode may be used as a control electrode for the purpose.

Since radiative cooling must be used for dissipation, heat must be conducted from tube elements to suitable radiators. At the present time, the most likely method for achieving this appears to be through use of heat pipe systems.

TUBE LIFE

The desired life of the microwave tube device to be used in the SPS system is 30 years or more. Life histories of most microwave tubes fall far short of this figure. One high power klystron, the Varian VA-842, has shown potential for a comparable operating life. The VA-842 is a 75 kW average power output and 1.25 MW peak power output pulsed UHF klystron. The

operating pulse width is 2.0 milliseconds. The electron gun design includes
a mod-anode. Cathode emission density and operating temperature are
moderate.

Table 4 shows data extracted from the USAF "Electron Inventory Report"
of 30 June 1979. Four VA-842 klystrons, all still running, have accumulated
operational life figures of from about 14.1 to 16.5 years. Three other
long-lived tubes are listed as failing after approximately 11.1 to 13.8
years.

Table 4

VA-842 Klystron Life Data

Long-Lived VA-842 Klystrons

S/N	Status	Hours	Years
408	Still Running	144,883	16.5
393	Still Running	139,993	16.0
374	Still Running	133,469	15.2
511	Still Running	123,384	14.1
317	Failed 12/75	121,303	13.8
332	Failed 8/76	108,777	12.4
505	Failed 12/74	102,259	11.7

Calculated MTBF (68 tubes) = 37,748 hours

Data from USAF "Electron Inventory Report", 30 June 1979

The calculated mean time before failure (MTBF) for 68 VA-842 klystron
failures in use during the period 1964 to 1979 is 37,748 hours.

One key to long klystron life appears to be low cathode emission
density and moderate operating temperature. Use of a heated cathode is not
a deterrent to long life. Heater problems with VA-842 klystrons have been
insignificant.

CONCLUSIONS

Starting with the Varian VA-7773 klystron, state-of-the-art computations indicate that the basic efficiency may be improved by a few percentage points from 74% to possibly as high as 79% by lowering the electron beam microperveance to a value in the range of 0.2 to 0.35 micropervs, where the optimum product of electronic times circuit efficiency may be obtained. While improvement over known VKS-7773 performance would be modest, the relative importance of each percentage point in operating efficiency may justify the effort.

With a minimum acceptable microwave device efficiency of 85%, the additional efficiency points may possibly be realized through collector depression and recovery of energy from the spent electron beam. The achievement of 85% total efficiency will be a formidable task, yet the efforts of several workers[4,5,6,7] suggest that sufficient energy may be recovered by this means. If the many advantages of the klystron are to be applied, the importance of each point in efficiency would seem to require the investigation of collector depression.

Table 5 summarizes the advantages of the high efficiency klystron cw amplifier for space applications.

Table 5

Advantages of High Efficiency Klystron CW Amplifier

for Space Applications

1. High Gain Amplifier, 40 to 50 dB

2. High Power Output, 50 kW or more

3. High Efficiency, ~85% with collector depression

4. Low Noise Output Narrow bandwidth klystron

5. Low Harmonic Output Typically -30 dB or more from carrier

6. Long Life Potential ~16.5 years on record with one klystron type

7. Ease of Control and Protection with Mod-Anode Electron Gun Design

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