HIGH EFFICIENCY, CW, HIGH POWER KLYSTRONS FOR STORAGE RING APPLICATIONS*

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Summary

The 125 kW CW klystrons to be described in the first part of this paper were specifically designed for energy upgrading of the electron-positron storage ring, SPEAR II, at SLAC. Four tubes are required with an efficiency greater than 50 percent. The operating frequency is 358.54 MHz. The gain is approximately 50 dB, the operating voltage is 41 kV and the microperveance is 0.7. The klystron must be stable when working into an accelerator cavity VSWR as high as 2:1 at any phase angle. The calculated and experimental data to be presented include saturation and phase characteristics. A maximum efficiency of 57 percent was obtained and the highest output power was 160 kW CW at 42.5 kV. The second part of this paper deals with the design of a higher power version of this tube. The RF power is 500 kW CW at an efficiency exceeding 70 percent. The operating voltage and current are 62 kV and 11.5 A, respectively. The higher efficiency is obtained by inserting an additional cavity to make use of second harmonic bunching. Eighteen such klystrons are to be used in the proposed PEP storage ring.

Introduction

The SPEAR II klystrons are UHF CW tubes especially built for energy upgrading of the original storage ring at SLAC. Four tubes were installed in the ring during 1974. A fifth tube was built as a spare. These klystrons operate at the 280th harmonic of the particle circulation frequency in the storage ring, or 358.54 MHz. The design and performance of these tubes will be described.

The proposed PEP klystrons will be similar to the SPEAR II tubes, but will differ primarily in power output, efficiency and overall length. To date design calculations have been made and indicate that the goals can be met. Based on the close agreement observed between calculation and performance for the SPEAR II tubes, the PEP klystron design is considered to be realistic.

SPEAR II Klystron Design

The operating parameters for the SPEAR II klystrons are shown in Table I. It should be noted that a CW power level of 125 kW at an efficiency of 50 percent is formidable enough to require some care in the electrical and cooling designs. A microperveance as low as 0.7 was chosen in order to enhance the probability of obtaining an efficiency greater than 50 percent within an overall tube length of approximately 10 feet. An outline of the tube is shown in Fig. 1.

Table I

SPEAR II Klystron Operating Parameters

Frequency	358.54	MHz
Instantaneous Bandwidth (1 dB Points)	0.5	%
Beam Voltage	41	kV
Beam Current	6.2	A
RF Output Power	125	kW
Duty Factor		CW
Gain	50	dB
Efficiency	50	%
Load VSWR	Up to 2:1 at any phase angle	

The design of the klystron interaction space is quite conventional. Four cavities are used, resulting in a gain of approximately 50 dB. The low perveance chosen results in a higher beam impedance and hence a higher value of Q_L in the output cavity than is true in many other high power klystrons. This allows more options in the output coupling scheme. In the SPEAR II klystrons loop coupling is used. The output circuit consists of a short section of 3-inch diameter coax with the free end of the center conductor being surrounded by a ceramic cylinder. This cylinder, the inside of which has a thin Ti film, acts as the vacuum window. This whole structure forms the launching system in a reduced height WR-2100 waveguide. A single step and an inductive matching post are used to transform into standard WR-2100 waveguide.

Figure 2 shows a photograph of a SPEAR II klystron. The output window and cathode seal make use of the same ceramic bushing, which incidentally is used for the cathode seal on all SLAC S-band klystrons. The collector requires a water flow of 50 gpm, while the body and RF output system require approximately 2.5 gpm. All cavities, drift tubes, the anode and the window along with the RF output inner and outer conductors are water cooled. The klystron operates in a focusing system of approximately 150 gauss, which is 2.5 times the Brillouin field. The whole package stands vertically with the gun-end down. The cathode socket and seal are under oil.

The gun utilizes a convergent Pierce-type design. The cathode diameter is five inches and the area convergence is 6.75 to 1. This represents a cathode loading of only 50 mA/cm^2 at operating conditions. An oxide coated cathode supplies this current density comfortably.

A one dimensional large-signal digital computer program was used to calculate the performance of the SPEAR II klystron design. This program has agreed quite closely with experimental results in the past. A maximum

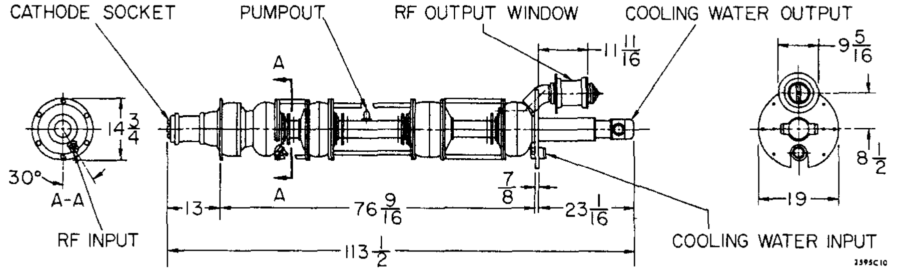

FIG. 1--SPEAR II klystron outline.

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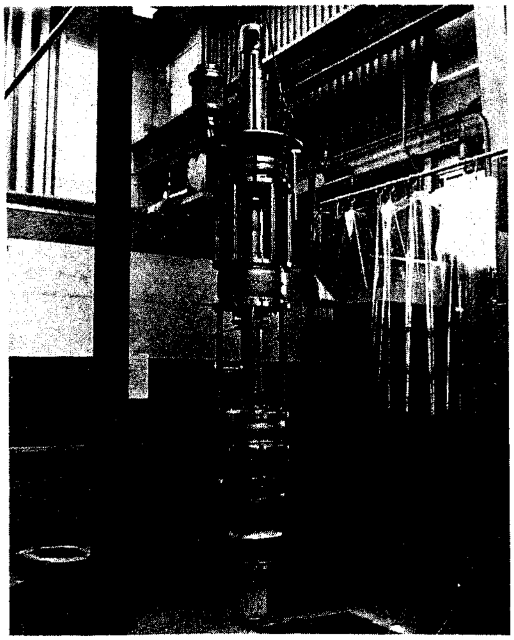

FIG. 2--SPEAR II klystron.

efficiency of 59 percent was calculated for 41 kV. The maximum output power and efficiency are plotted as a function of voltage in Fig. 3.

SPEAR II Klystron Performance

The first SPEAR II klystron was tested during the early part of 1974. Four additional tubes have since been completed and tested. The experimental data reported in this paper are based on the first tube, although subsequent tubes performed substantially the same. Along with the curves calculated for Fig. 3 there are shown experimental points for the output power and efficiency. The highest power output levels can be obtained with nonuniform focusing of the electron beam. The nonuniform focusing leads to some beam interception in the final drift tube and the output gap.

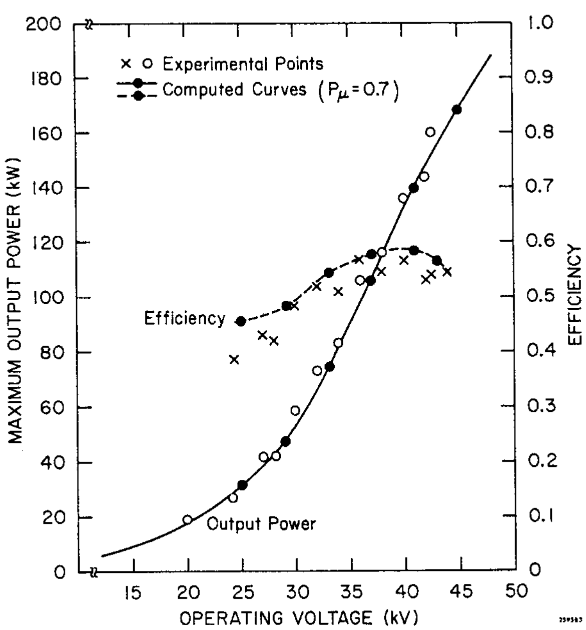

FIG. 3--Output power and efficiency vs operating voltage for SPEAR II klystrons at 358.5 MHz.

Furthermore, oscillation power of a few kW is generated in the tube when no drive signal is present at voltages above 39 kV. For these reasons a more uniform magnetic focusing field is chosen. This reduces the interception and eliminates the oscillations, but the efficiency is between 50 and 53 percent at 40 kV.

The output power as a function of drive power is shown in Fig. 4 for several frequencies. These curves were obtained with the tube operating into a matched load, but the performance was similar when the klystron worked into an accelerating cavity.

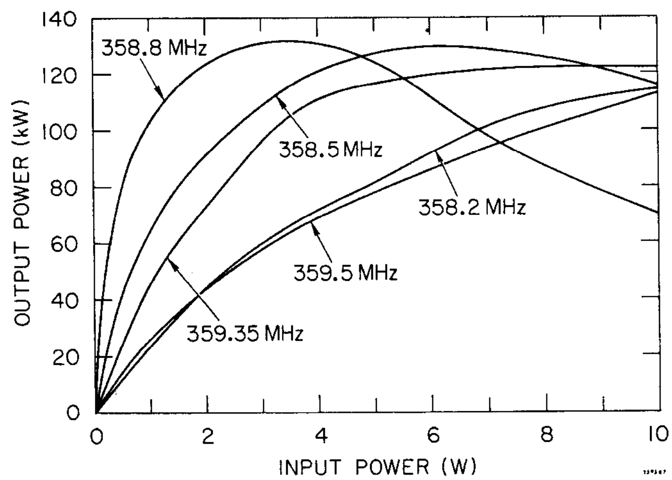

FIG. 4--Transfer characteristics for SPEAR 1B klystron (focusing field optimized for maximum stability and low beam interception at 40 kV).

Figure 5 indicates phase excursions of 20° to 40° at a fixed voltage and various frequencies as the power is varied

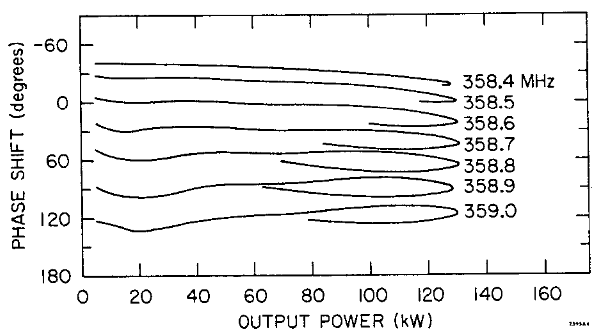

FIG. 5--Measured phase shift vs output power for SPEAR II klystrons. $V_0 = 40$ kV.

from low level through saturation and beyond. This agrees well with calculated values. Saturation occurs for each frequency shown at the point farthest to the right. Note that the total phase shift through the tube is in the order of 1500 to 2000 degrees. Thus, as the beam voltage is swept over the desired operating range of 25 to 40 kV, the total phase shift decreases by several hundred degrees.

PEP Klystrons

Table II compares the proposed PEP klystron design with that for the SPEAR II tubes. The major klystron design problems in going from SPEAR II to PEP involve the increase in efficiency, the RF window and the collector. The first two items represent significant extensions of the state of the art at the 500 kW power level. In the PEP klystrons a fifth cavity will be added in order to improve the

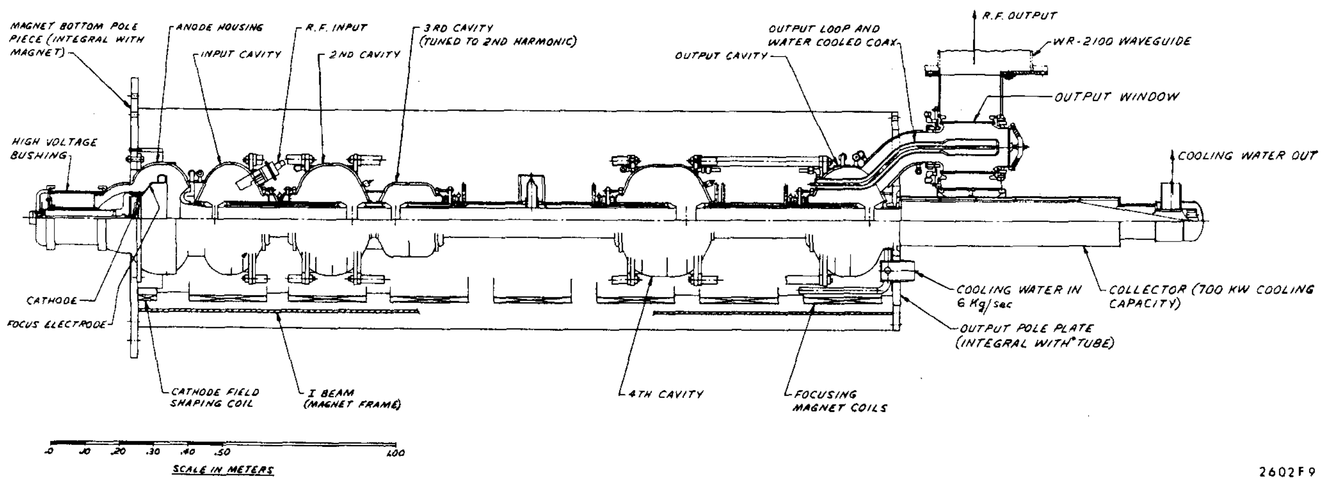

FIG. 6--PEP klystron and magnet assembly.

Table II

SPEAR II and PEP Klystron Parameters

	SPEAR II Klystrons	PEP Klystrons
Frequency	358.54 MHz	358.54 MHz
Inst. Bandwidth (1 dB Points)	0.5 %	0.5 %
Beam Voltage	41 kV	62 kV
Beam Current	6.2 A	11.5 A
Beam Power	250 kW	713 kW
RF Output Power	125 kW	500 kW
Drive Power	5 W	15 W
Saturation Gain	44 dB	45 dB
Efficiency	50 %	70 %
Load VSWR	Up to 2:1 at any phase angle	
Magnetic Focusing Field	150 G	150 G
Ratio of Beam-Drift Tube Radii	0.7	0.7
Number of Cavities	4	5
Overall Length	290 cm	350 cm

efficiency. This cavity is tuned to the second harmonic. It is placed in the interaction space as shown in the schematic diagram for the PEP klystron in Fig. 6. The position and phasing of the second harmonic cavity are chosen so as to maximize the number of electrons entering the output cavity during the retarding half-period of the RF wave.[1] It was suggested by Guénard et al.[2] that if an electron beam could be bunched with a saw-tooth voltage, it should be possible to arrange matters so that all the electrons passing through the input cavity within one cycle arrive together at the output. Since it is not possible to achieve saw-tooth bunching with existing circuit means, an attempt may be made to build up the saw-tooth from a Fourier series. This may be accomplished by coupling harmonic cavities to the beam.[3] Such an approach has been utilized by Lien[4] in order to obtain a significant increase in efficiency. For the PEP klystron, design calculations indicate that the interaction space parameters shown in Table III increase the efficiency from approximately 60 percent to slightly above 70 percent. It should be noted that the drift lengths chosen are based on the SPEAR II klystron design, where a ten foot length restriction had been imposed. For the PEP tubes this also results in a relatively short tube at this frequency.

Table III

PEP Klystron Interaction Space Parameters

Cavity Number	R/Q	Q	Gap Transit Angle (Rad)	Gap Voltage at 500 kW (kV)
1	85	1000	0.274	1.0
2	90	3000	0.726	8.4
3 (2nd Harm)	74	2000	0.839	4.5
4	115	3000	1.232	24
5	85	83	0.433	90

Drift Space Number	Reduced Plasma Wavelengths (Degrees)	Length (cm)
1	27	44.8
2	7.08	12.6
3	58.8	88.0
4	36.1	54.0

Details of the efficiency calculations are shown in Fig. 7. For 60 kV an efficiency of 71.6 percent was obtained. Gain and power output as a function of input power are shown in Fig. 8 for several values of operating voltage. Note that 500 kW of output power should occur at 62 kV with a drive power of approximately 11 watts. For completeness a series of curves for the phase shift are included in Fig. 9. Note that the phase shift from low drive to saturation varies by approximately 20°. The phase shift appears to decrease slightly at the voltage where harmonic bunching is most effective.

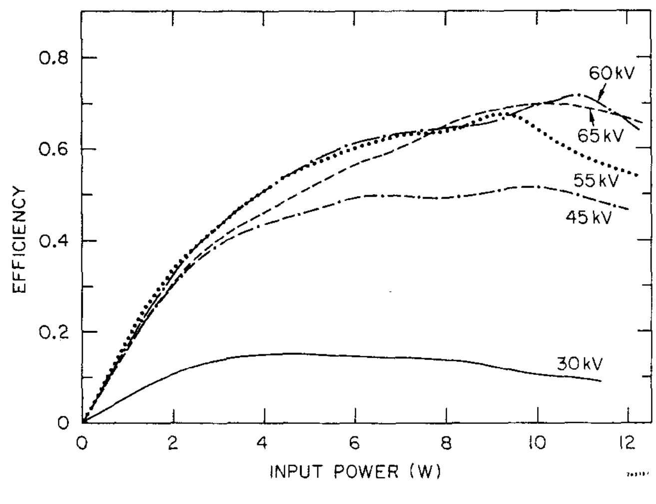

FIG. 7--Calculated efficiency vs drive power for PEP klystron.

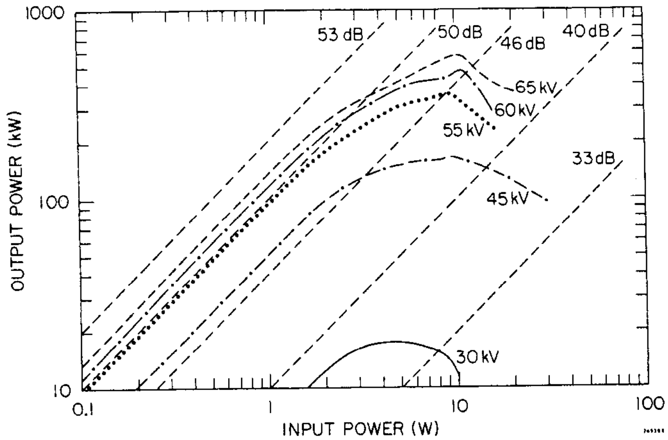

FIG. 8--Calculated transfer characteristics for PEP klystron.

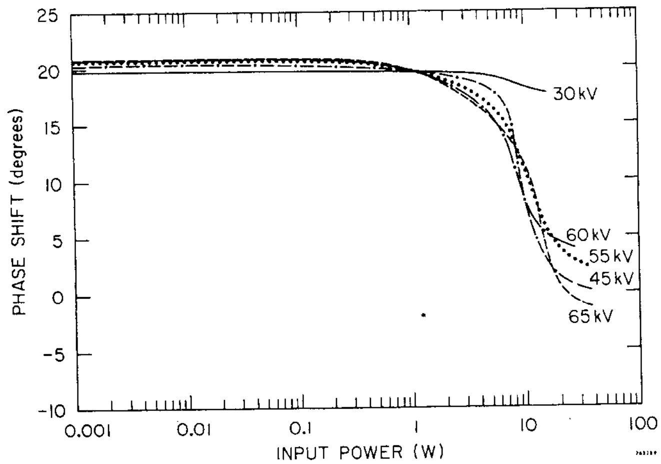

FIG. 9--Calculated phase shift vs drive power for PEP klystron.

References

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