PERFORMANCE OF A HIGH EFFICIENCY HIGH POWER UHF KLYSTRON*

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Summary

A 500 kW CW klystron has been designed for the PEP storage ring at SLAC. The tube operates at 353.2 MHz, 62 kV, a microperveance of 0.75, and a gain of approximately 50 dB. Stable operation is required for a VSWR as high as 2:1 at any phase angle. The design efficiency is 70 percent. To obtain this value of efficiency a second harmonic cavity is used in order to produce a very tightly bunched beam in the output gap. At the present time it is planned to install 12 such klystrons in PEP. A tube with a reduced size collector was operated at 4 percent duty at 500 kW. An efficiency of 63 percent was observed. The same tube was operated up to 200 kW CW for PEP accelerator cavity tests. A full-scale CW tube reached 500 kW at 65 kV with an efficiency of 55 percent. In addition to power and phase measurements into a matched load, some data at various load mismatches are presented.

Introduction

The need for klystrons capable of supplying high CW RF power for a storage ring can be met by several designs. One way would be to scale simply the SPEAR II UHF klystrons[1] operating at 358.5 MHz with a power output of 125 kW at 50 to 55 percent efficiency. If this were done, then, for the 500 kW PEP klystrons, the dc input power to each klystron would be close to 1 MW. In view of the scarcity and high cost of power, this is not an attractive approach. Computer calculations indicate that an efficiency of somewhat greater than 70 percent should be achievable in a 500 kW tube. The dc input power per tube would then be 715 kW, reducing by 2.5 MW the total installed power capacity for the 12 stations proposed.

Two tubes, as well as a beam tester diode, have been built to date and tested. Both the predicted and actual performance will be described in this paper.

PEP Klystron Design

The operating parameters for the PEP klystrons are shown in Table I.

TABLE I

PEP Klystron Operating Parameters

Frequency	353.2 MHz
Instantaneous Bandwidth (1 dB points)	0.5%
Beam Voltage	62 kV
Microperveance	0.5
RF Power Output	500 kW
Efficiency	0.7
Drive Power	12 W
Saturation Gain	46 dB
Load VSWR	Up to 2:1 at any phase angle
Magnetic Focusing Field	175 gauss
Ratio of Beam-Drift Tube Radii	0.7
Number of Cavities	5
Overall Length	3.6 m

It is apparent that the requirement of 70 percent efficiency implies some careful optimization of the design. Furthermore, an average power level of more than $\frac{1}{2}$ MW within a single device requires careful consideration of all cooling needs. A microperveance as low as 0.75 was chosen in order to enhance the probability of obtaining a high efficiency within a reasonable tube length. The photograph in Fig. 1 shows the tube and associated components.

A large signal analysis using polarization variables developed by T. Wessel-Berg[2] was used in the electrical design of the klystron interaction space. It was found that a conventional multicavity klystron design would not yield an efficiency of 70 percent. With a second harmonic cavity, however, a peak efficiency of 71 percent was indicated. Some time ago Guénard et al.[3] suggested that if an electron beam could be bunched with a sawtooth voltage, it should be possible to arrange matters so that nearly all the electrons passing through the input cavity within one cycle arrive together at the output gap. Beck mentioned a scheme[4] wherein the position and phasing of higher harmonic cavities are chosen so as to maximize the number of electrons entering the output cavity during the retarding half-period of the RF wave. Lien has utilized this approach in order to obtain a significant increase in efficiency.[5] For the PEP klystron, for example, design calculations indicate that the presence of a second harmonic cavity increases the efficiency from approximately 60 percent to slightly above 70 percent. The pertinent electrical design parameters are shown in Table II.

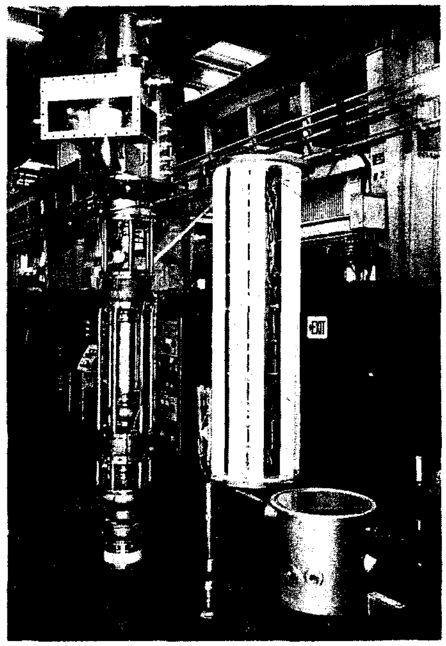

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Fig. 1. PEP 2 Klystron with focusing magnet and high voltage tank.

TABLE II

PEP Klystron Interaction Space Parameters

Cavity Number	Cavity Frequency (MHz)	Q	Gap Transit Angle (Rad.)	Gap Voltage at 500 kW (kV)
1	353.4	1000	0.270	1.0
2	354.3	3000	0.715	8.4
3 (2nd Harm.)	705.7	2000	0.827	4.5
4	359.0	3000	1.214	24
5	352.5	83	0.427	90

Drift Space Number	Reduced Plasma Wavelength (Degrees)	Length (cm)
1	29.9	45.5
2	8.42	12.8
3	58.8	89.3
4	35.1	53.3

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This design meets all the operating parameters listed in Table I. An outline drawing of the first PEP prototype klystron is shown in Fig. 2. The overall length is slightly greater than 3.5 m.

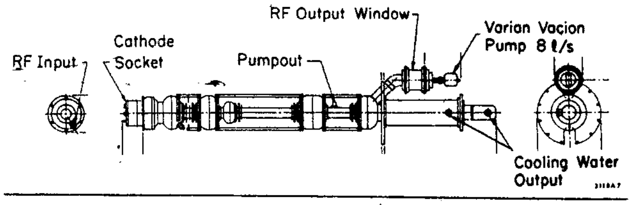

Fig. 2. Outline drawing of PEP 2 Klystron.

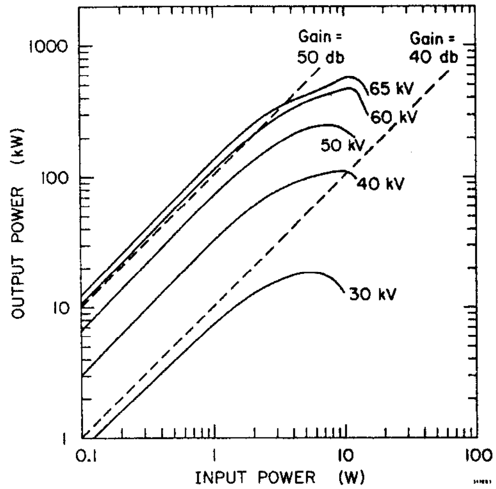

Fig. 3. Calculated transfer characteristics for PEP Klystron. (f_0=353.2 MHz.)

Figure 3 shows the computed performance of the PEP klystron. Note that 62 kV and a drive power of 12 W are needed for an output power of 500 kW. A gain of 46 dB at saturation is indicated, while the small signal gain is slightly above 50 dB.

A coaxial line is used for the output circuit. The center as well as the outer conductor of this coax is water-cooled. The center conductor, which is 3.35 cm in diameter, extends through the output cavity and forms the coupling loop. The rest of the output circuit consists of a short section of 8.6 cm diameter coaxial line with the free end of the center conductor being surrounded by a 20 cm diameter ceramic cylinder. The cylinder, the inside of which has a thin Ti film for multipactor suppression, acts as the vacuum window. This whole structure forms the launching system in a reduced height WR-2100 wave guide. A single step and an inductive matching post are used to transform into standard WR-2100 wave guide.

All cavities, drift tubes, the anode, the metal parts of the window, and the output circuit are water-cooled with an average flow of 0.35 ℓ/s, while the collector requires 6 ℓ/s. The klystron is designed to operate in a focusing system of approximately 175 gauss, which is 2.5 times the Brillouin field.

The solid electron beam is formed in a convergent Pierce-type gun. The cathode diameter is 12.5 cm and the area convergence is 6.75 to 1. This represents a cathode loading of 85 mA/cm^2. An oxide-coated cathode supplies this current density comfortably.

PEP Klystron Performance

To date three devices have been built in the development of the PEP klystrons. The first was a diode containing a gun and a full-scale collector. It served two functions: to prove the collector power dissipation capability and to serve as a convenient load for power supply tests. It was operated up to 750 kW and indicated the need for some minor mechanical design changes in the collector.

First, due to power supply and bake oven limitations, a pulsed klystron was built. It was designated PEP 1C and could operate up to 4 percent duty. At 60 kV a power output of 440 kW and at 65 kV a power output of 520 kW were observed. This represents an efficiency of 63 percent. In addition, this tube was used for accelerator cavity tests up to 200 kW CW.

A full CW tube, designated PEP 2, was also built. This tube achieved 500 kW CW at 65 kV with an efficiency of 55 percent. With RF drive removed the collector was tested up to a power dissipation level of 820 kW. This is a necessary mode of operation in the PEP application, since the klystron output power is to be controlled by varying the RF drive.

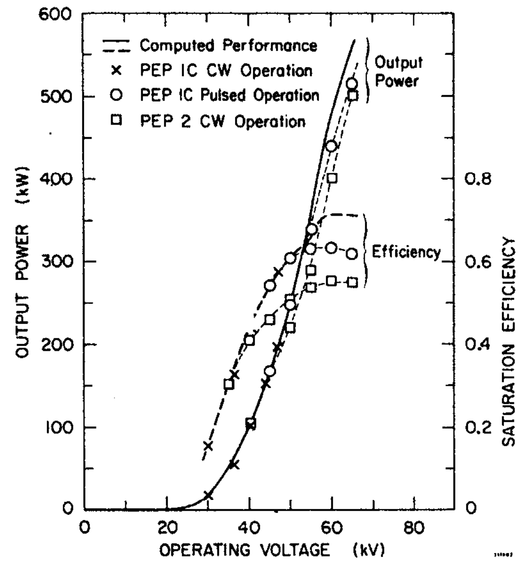

Fig. 4. Computed and experimental performance of PEP klystrons. (f_0=353.2 MHz; P_{in} = 12 W; $B_0 \cong$ 180 gauss.)

Figure 4 compares the actual performance of the two klystrons (points) with the computed values (curves). Note that at lower voltages the agreement is very good while at higher voltages the actual power output is less than predicted. The deviation is greater for the full CW tube. The output power and the change in phase across the tube are plotted as a function of drive power in Fig. 5. These data were taken at 60 kV with the focusing field adjusted for optimum stability. Note that the phase change is approximately 20° from low drive to saturation. This is in fair agreement with the

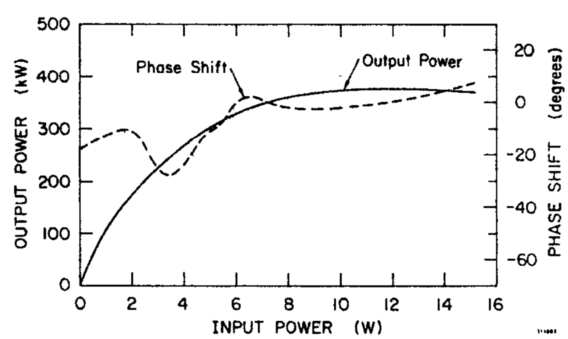

Fig. 5. Output power and phase shift vs drive power for PEP 2 Klystron. (f_0 = 353.2 MHz; B_0 = 180 gauss; V_0 = 60 kV.)

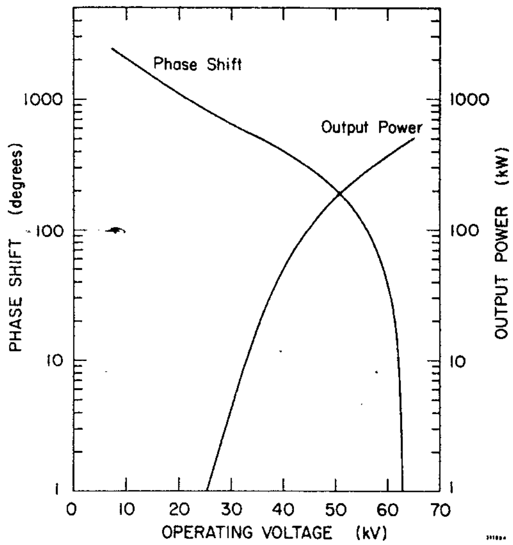

Fig. 6. Phase shift and output power vs beam voltage for PEP 2 Klystron. (f_0 = 353.2 MHz; $B_0 \cong 180$ gauss; P_{in} = 12 W.)

computed results. Figure 6 shows the variation of output power and phase shift as the operating voltage is varied. A constant drive power of 12 W was used and the magnetic field was held constant.

The tuning of the second harmonic cavity is quite critical for optimizing the efficiency. Figure 7 shows a series of

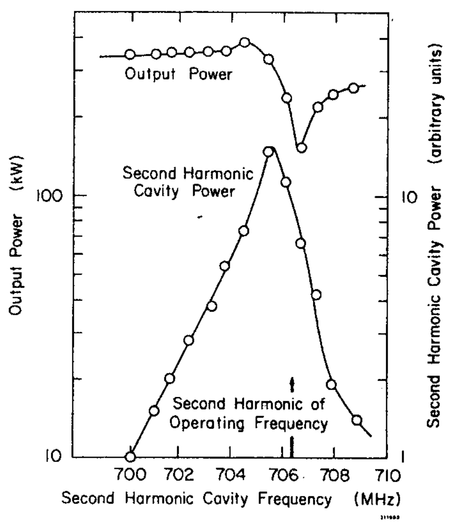

Fig. 7. Performance of PEP 2 Klystron as a function of 2nd harmonic cavity tuning. (V_0 = 60 kV; f_0 = 353.2 MHz.)

points for klystron output power and second harmonic cavity power level as the cavity tuning was changed in discrete steps. The computer program predicts an optimum cavity tuning frequency of 705.7 MHz, while in practice a frequency of 704.5 MHz was found to work best. This discrepancy could be due to the fact that the microperveance of the tube is 0.815 instead of the design value of 0.75. This aspect will be studied in more detail when PEP 2 is rebuilt.

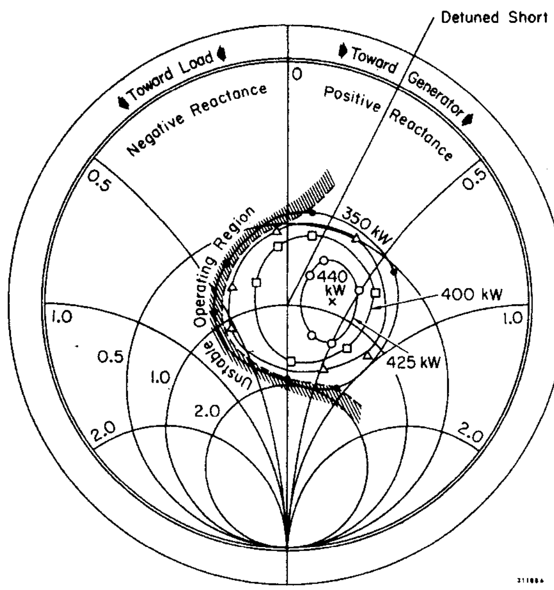

Fig. 8. Performance of PEP 1C Klystron into a variable load. (V_0 = 60 kV; f_0 = 358.5 MHz.)

The last figure, Fig. 8, is an example of the klystron stability studies as the magnitude and phase of the load reflection coefficient are varied. At 60 kV the VSWR for maximum power output is seen to be 1.45:1. These data were obtained on the pulsed tube, but much more extensive studies are planned for the CW tubes. The reason that the optimum VSWR is not nearer to the center of the Smith Chart is two-fold. First, the output cavity coupling loop in the pulsed PEP tube is identical to that used in the SPEAR tubes. Therefore, the output cavity is undercoupled. The output cavity is undercoupled further because the perveance in the pulsed PEP tube is slightly high.

Conclusions

The collector and RF window capabilities for the PEP klystron have been proven up to the design value of 500 kW. The output Q has not been correct because of a slightly high perveance. In addition, the high perveance also resulted in the wrong space charge conditions in the beam. This had an adverse effect on the second harmonic cavity performance.

One further observation was made on the full power CW tube. The short section of drift tube between the output gap and the collector dissipates too much power when the focusing field is adjusted for maximum output power. This indicates the beam is somewhat scalloped, probably due to a wrong magnetic field profile in the gun region. If the scalloping is adjusted to get the beam through the last drift tube, it is also too thin in the output gap, resulting in a poor coupling coefficient. These items will all be corrected when PEP 2 is rebuilt.

References

1. G. T. Konrad, "High Efficiency, CW, High Power Klystrons for Storage Ring Applications," IEEE Trans. Nucl. Sci. NS-22, 1249-1252 (June 1975).
2. Unpublished work.
3. P. Guénard, R. Warnecke, and C. Fauve, "Sur le rendement des tubes a modulation de vitesse," Ann. Radioélec. 3, 302-327 (1948).
4. A.H.W. Beck, Space-Charge Waves and Slow Electromagnetic Waves (Pergamon Press, New York, 1958), p. 205.
5. E. L. Lien, "High efficiency klystron amplifiers," 8th Int. Conf. on Microwaves and Optical Generation and Amplification, Amsterdam, 7-11 September 1970 (Kluwer, Deventer, Netherlands, 1970), pp. 11-21 to 11-27.