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150-MW S-Band Klystron Program at the Stanford Linear Accelerator Center[1]

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Abstract. Two S-Band klystrons operating at 150 MW have been designed, fabricated and tested at the Stanford Linear Accelerator Center (SLAC) during the past two years for use in an experimental accelerator at Deutsches Elektronen Synchrotron (DESY) in Hamburg, Germany. Both klystrons operate at the design power, 60 Hz repetition rate, 3 μs pulsewidth, with an efficiency > 40 %, and agreement between the experimental results and simulations is excellent. The 535 kV, 700 A electron gun was tested by constructing a solenoidal focused beam-stick which identified a source of oscillation, subsequently engineered out of the klystron guns. Design of the beam-stick and the two klystrons is discussed, along with observation and suppression of spurious oscillations. Differences in design and the resulting performance of the klystrons is emphasized.

INTRODUCTION

One possible candidate for future collider work relies on proven S-Band technology and is being studied at Deutsches Elektronen Synchrotron (DESY). The prototype for this system, currently under test at DESY, utilizes two 150 MW klystrons built at SLAC. Both of these klystrons were developed by extending the existing 50 MW S-Band klystrons to higher beam current and rf power densities.

Since the end result of the SLAC development was to construct two viable klystrons, the design philosophy followed a rather conservative approach. The rf stresses on the window and load ceramics and the rf voltages in the cavities and on matching elements were all kept at or below levels found in the current SLAC 50 MW S-band production tubes. The pulse energy of 450 Joules is the highest published energy per pulse for a 100 MW-level (or greater) tube, but the average power is roughly identical to that experienced in the production tube since the repetition rate is only 60 Hz. Gun voltage gradients, cathode emission density,

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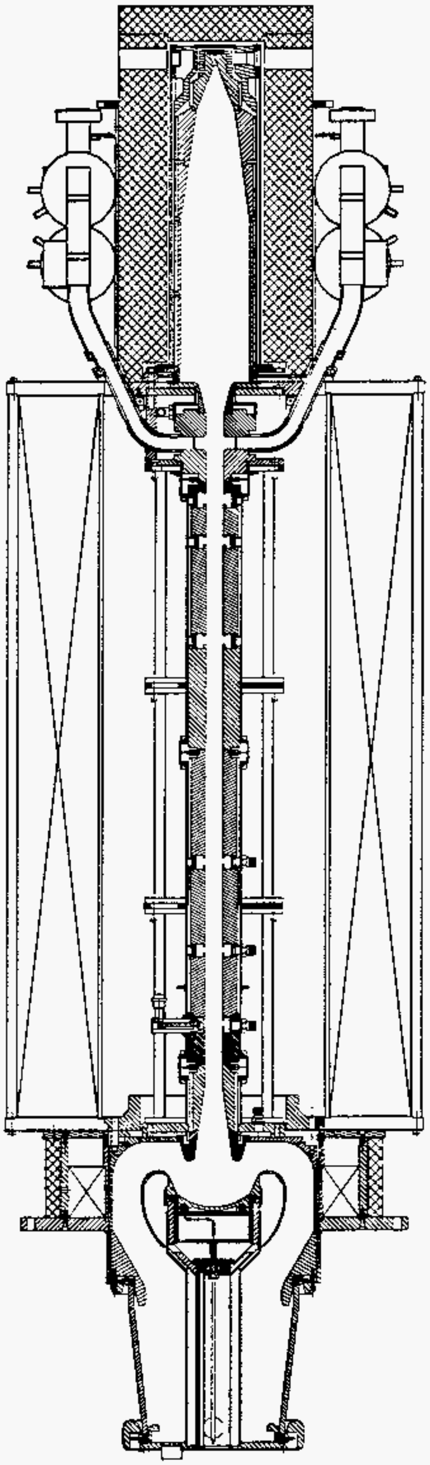
focus electrode temperature, peak and average collector current and power density were also kept at or below the production tube levels. The drift tube diameter was not changed and therefore beam power and current densities were higher, forcing a higher convergence of the gun and greater focusing field. The higher current density can often lead to spurious oscillations which arise from noise during pulses of sufficient length. Such oscillations, and other less-understood beam phenomena with various effects upon the rf pulse, were studied in the first klystron and several ideas were adopted in the design of the second klystron which appeared to reduce unwanted oscillations significantly. Some of the design changes have been adopted in later high power klystrons built at SLAC such as the latest 50-MW X-band klystron XL-4. An outline drawing of the klystron is shown inserted into the 15-kW solenoid and dressed with collector lead (Fig. 1).

BEAM-STICK

A solenoid-focused beam-stick was built to test the beam-optics of the klystron gun design. The same gun used in the beam-stick was also used in both klystrons (Fig. 1) with slight modifications described later. The cathode support and focus electrode are oil-cooled via a tube and pump set in the pulse tank. The gun proved very robust during processing and came up to full power at 1 μs very quickly. Microperveance was measured at 1.78 at the design voltage and beam transmission was 99.8%. At 3 μs pulsewidths and near full power operation, a powerful oscillation at 1.365 GHz of at least 1 MW, and probably 10's of MW, would appear at the end of the pulse. It was later determined that the oscillation existed inside the focus electrode and so design changes were made to the klystron gun to eliminate the coupling to the outside world. Both changes involved insertion of material to short out possible cavities within the gun, one at the focus electrode and one at the cathode edge.

KLYSTRON DESIGN

The two klystrons each have an input cavity, two gain cavities, three buncher cavities, and an output structure. The six cavities are all of conventional re-entrant design. The output structure is a single-gap pillbox in the first klystron and in the second klystron a 2-cell standing-wave structure is used. Both klystrons use essentially identical gun, rf section and collector designs with a few exceptions. The second klystron has two stainless steel drift tubes in the buncher section and utilizes the 2-cell output structure. The gun of the second klystron uses a scandate cathode instead of an M-type cathode and has the cathode-edge shorting fingers



Design Parameters

Beam Voltage	535 kV
Beam Current	700 A
RF Pulsewidth	3 μs @ 60 Hz
Cathode loading	2:1 (6 A/cm^2 max)
Area convergence	40:1 (5.25" dia.)
RF Output Power	150 MW
Saturated gain	~55 dB
Efficiency	> 40%
Frequency	2998 MHz
Focusing field	< 2100 gauss

Figure 1: DESY 150 MW Klystron *1

removed (the cathode-edge shorting fingers were used in the first klystron to eliminate a possible source of oscillation but later deemed not essential).

Power is extracted through two waveguides to help eliminate asymmetries in the output structure. Each waveguide splits the power through two windows thus each of the four windows transmit approximately 38 MW. Power is recombined into two waveguides and each waveguide will drive one input of the test accelerator at DESY. Waveguide components and windows are the same devices as are found on the 2856 MHz 50-MW klystron but tuned to the slightly higher DESY operating frequency of 2998 MHz.

KLYSTRON EXPERIMENTAL RESULTS

The first klystron processed normally and without the gun oscillation seen in the beam-stick. The tube was capable of more than 160 MW at the design voltage. The saturated power data (Fig. 2) was obtained by optimizing the settings for maximum output at a specific beam voltage when operating at 3 μs. The peak power was obtained at the design frequency of 2.998 GHz within a couple MHz, and was found using a calorimetric method. The reason that the curve (Fig. 2) is not smooth is due to avoidance of the oscillation described in the following paragraph.

An 8.65 GHz oscillation was detected after the rf pulsewidth was extended to 3 μs. The oscillation, if left unchecked, would be followed by large gas bursts and notches in the collector current as the beam impacted the drift tube or a cavity. It is also present with and without rf drive, and is fairly insensitive to the amount of

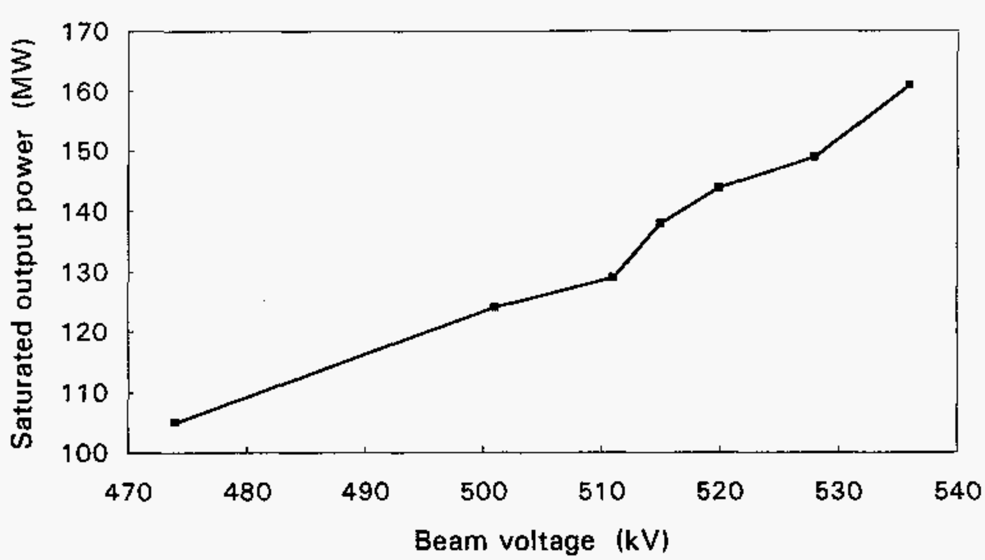


FIGURE 2. Saturated output power versus beam voltage for the first 150 MW klystron.

TABLE 1. Performance highlights of the second 150 MW klystron

Efficiency	>45 % at 150 MW output power
Pulsewidth	3 μs pulsewidth at 450 J pulse energy
Gain	55 dB saturated gain
Wavelength	10 cm operation
Stability	No oscillations at design points

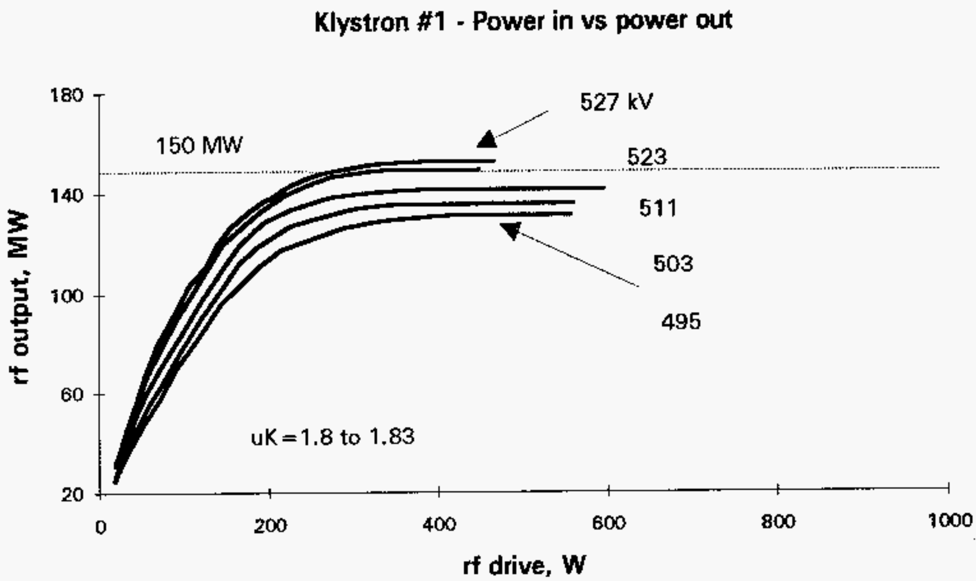
drive. The oscillation exhibits a periodicity with magnetic field and beam current where at higher beam currents only lower values of confining field would allow safe operation. In order to operate the tube at full power at long pulsewidths it is necessary to choose a value of confining field for operational stability. Simulation shows the 8.65 GHz mode to be present along most of the drift tube and strongest in the buncher cavities. To increase the rf loss and hence increase stability, two stainless steel drift tubes were inserted in place of the standard copper drift tubes in the second klystron.

The second klystron processed very quickly and exhibited none of the instabilities previously observed during normal operation. Operation at full specification was achieved at slightly higher efficiency (Table 1) than predicted. An observation was made at power levels below saturation of an instability which would occur at any point in time across the pulse. The manifestation was as an increase in collector current without disturbing the gun voltage or current waveforms. This was thought to be some secondary emission and the most likely candidates were perhaps either the collector or the stainless steel drift tubes. This phenomena did not interfere with saturated output performance and perhaps more information will be available after several thousand hours of operation at DESY. The peak power at saturation coincided with the design frequency and the large signal gain was approximately 55 dB. The output pulse was flat to 0.2 dB across approximately 3 μs. The reason for the ripple was due to variations in beam voltage of about 18 kV at the beginning of the flattop.

COMPARISON OF KLYSTRON 1 AND 2

The second klystron has a slightly lower gain and higher efficiency than the first klystron (Fig. 3) which can be attributed to the 2-cell output structure. The tube could be expected to reach power levels above 160 MW but was not tested since the program was not pure research and the klystrons were required for the test accelerator. Both tubes appeared stable in the overdrive regime for at least a few dB. The first klystron however, suffered from the drift tube oscillations if saturation was pushed too far, and the second klystron ran out of drive power at about 1 kW. The different cathodes lead to different beam current density profiles which alter the beam-cavity interaction and this also has an affect on the shape of the two sets of curves.

Emission data for both klystrons is plotted (Fig. 4) verses heater power. The curve for klystron #2 shows the moderate slope of a scandate cathode which is



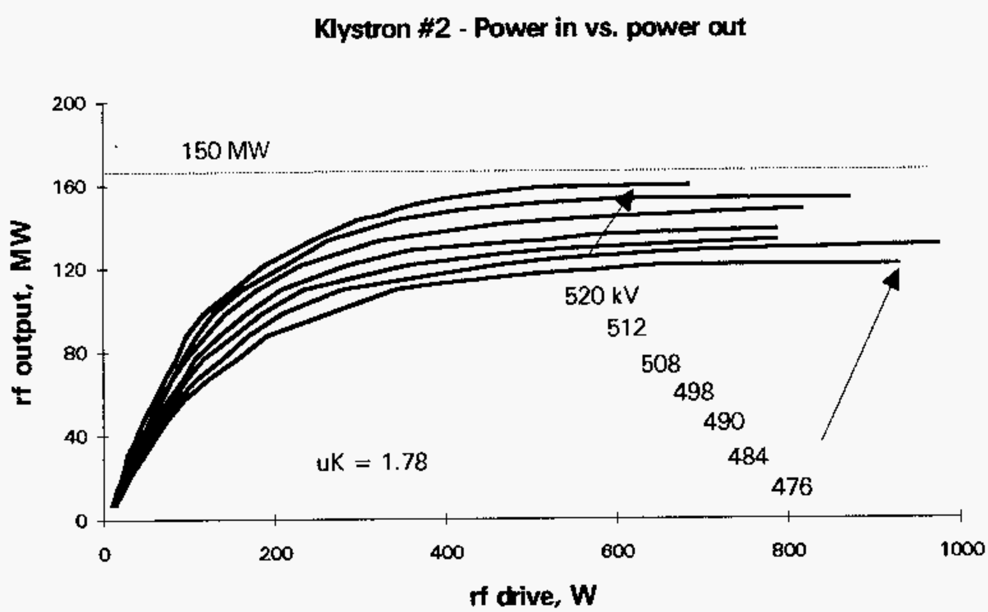


FIGURE 3. Output power for both klystrons as a function of rf drive at various beam voltages.

similar to typical data of the SLAC 5045 klystron. The klystron #1 curve for the M-type cathode shows a sharper emission curve and a requirement for 30 % more heater current and almost twice the power. Data manipulation gives a "Practical Work Function Distribution" (G. Miram) which peaks at 1.78 for the M-type. Results of the beam-stick testing, which was also an M-type, agree closely with that of the first klystron.

Though statistically insignificant, both the beam-stick and the first klystron used M-type cathodes and require about 36 A to operate fully space-charge-limited while the second klystron with a scandate cathode required only 27 A. The gallery 5045 klystrons also have scandate cathodes and require about 30 A on average for a beam with 57 % of the current (at approximately the same current density) of the 150 MW klystrons. The soft "knee" of the scandate emission curve has been associated with greater stability with many high power klystrons and also allows for less sensitivity to heater fluctuations when operation near the knee is desired or necessary.

Both klystrons exhibited the same higher frequency preference in small signal gain response (Fig. 5), approximately 65 dB at 3.010 GHz, or 12 MHz higher than the design value. However, the final design step for both klystrons was to vary the geometry to achieve a power peak at 2.998 GHz at saturation according to simulation. Both klystrons exhibited a shift in the gain vs. frequency curve as saturation was approached so that saturated gain was very close to design as seen (Fig. 6) for klystron #2 (data for #1 was unavailable but essentially the same). The rf output power peaked within 1 MHz of the design value for both klystrons as well. The roughness of the curve for klystron #1 is due to the adjustment of magnetic field as the beam voltage was varied to avoid the oscillation areas as explained earlier.

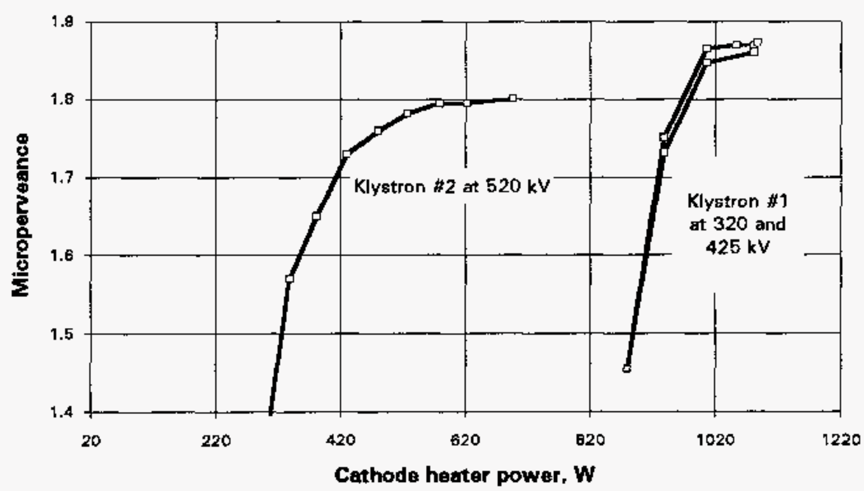


FIGURE 4. Microperveance as a function of heater power for klystron #1 and klystron #2.

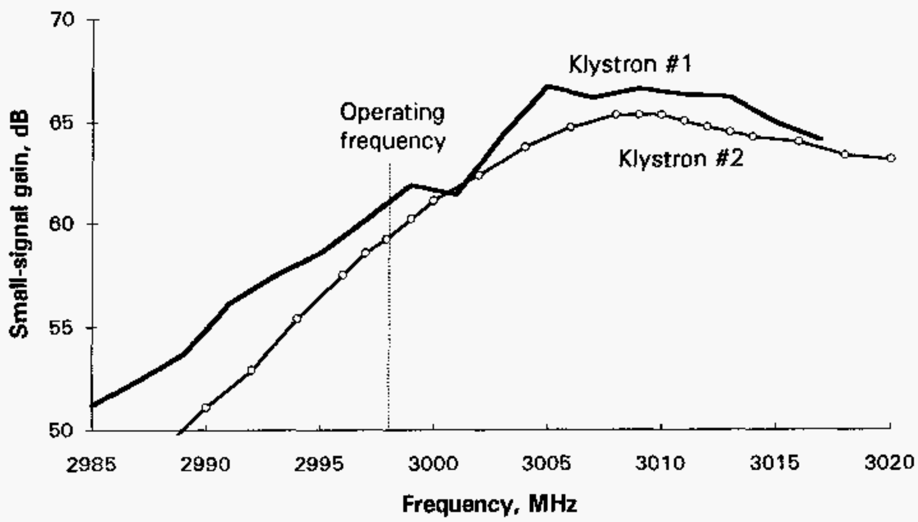


FIGURE 5. Small signal gain response for klystron #1 and klystron #2

Efficiency is difficult to measure due to the summation of uncertainties in gun voltage and current, intercepted power, collector current and power, rf output power and waveguide losses in these high power tubes. Knowing the gun voltage and current across the pulse better than 2 % is difficult, hence beam power from the gun may have as much as a 4 % error. RF output power can also be difficult but values can generally be determined to within 3 % by using calibrated flow

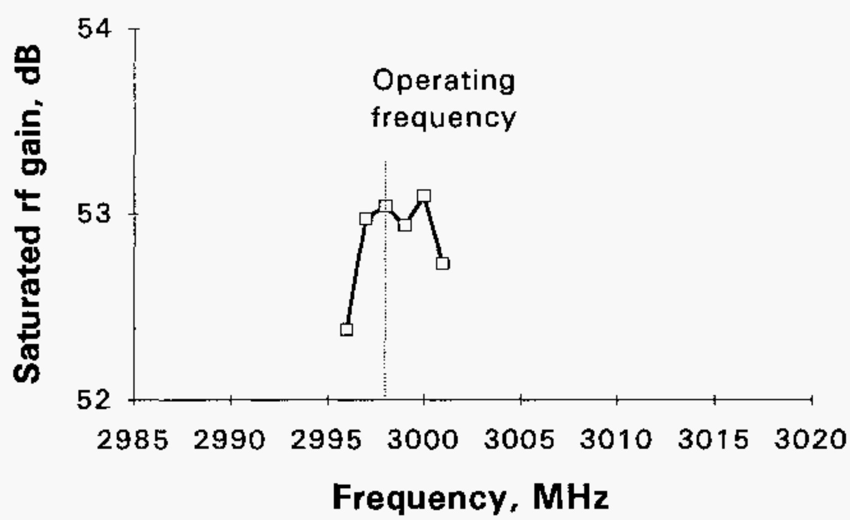


FIGURE 6. Large signal gain response for klystron #2.

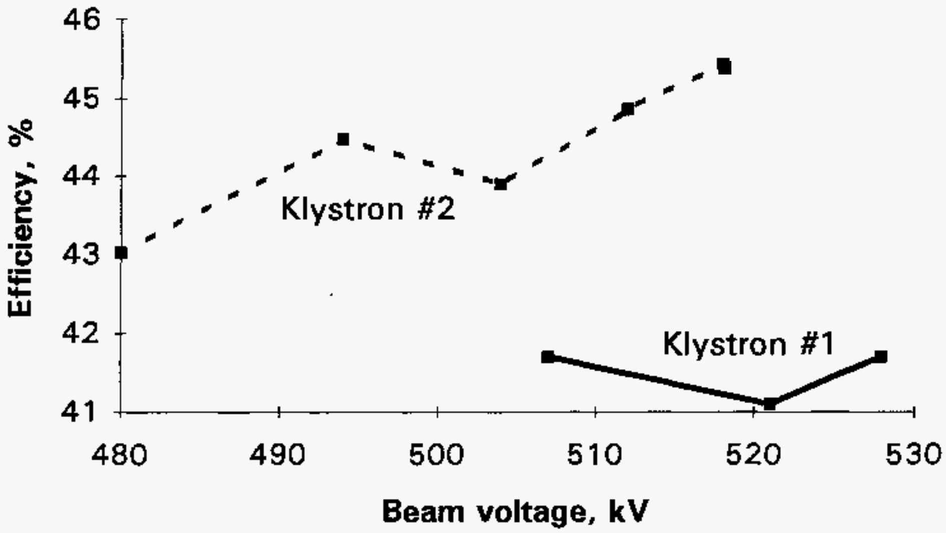


FIGURE 7. Efficiency measured at different beam voltages for both klystrons.

meters and delta-temperature measurements. With the preceding statements in mind, efficiency data was collected for both of the klystrons. It appears that klystron #2 has a few points of efficiency over klystron #1 (Fig. 6) which agrees well with simulation. This is attributed to the 2-cell output verses the single-gap output of klystron #1. The first klystron also has a larger amount of beam interception for a given amount of output power than the second klystron which also agreed quantitatively with simulation.

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The 150 MW S-band klystron development was a team effort and a natural evolution of existing SLAC technology. Many individuals are involved in producing such a tube and many others have interjected with valuable insights and considerable expertise:

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