KLYSTRON

The klystron is a very successful high-power microwave amplifier since it has good gain, over 40 dB; good efficiency, above 50%; good life expectancy, above 30,000 h, output power up to 150 MW pulsed for several microseconds, or 1.3 MW CW, and reasonable bandwidth of 5% to 15% (measured at rates slower than the response times of the cavities), but the instantaneous bandwidth is generally under a few percent. The klystron can be designed to operate with a center frequency between 200 MHz and 40 GHz, but the bandwidth of a single klystron is usually small. The lower frequency limit occurs only because of the impracticably large size of the klystron at large wavelengths, and the upper frequency limit arises from the difficulties in scaling the device with wavelength. The optimum frequency range for the high-power (above 100 kW) klystron is from 300 MHz to perhaps 20 GHz, but a few kilowatts of peak power can still be obtained up to 100 GHz. Special versions of the klystron—the extended interaction klystron and the hybrid klystron-traveling-wave amplifier—can provide several kilowatts power over 100 GHz.

OPERATION PRINCIPLE

The klystron is a vacuum electron device for transforming dc energy into RF energy, and it may be either an oscillator or an amplifier. In the past, small reflex-klystron oscillators were used as local oscillators in microwave receivers, but these oscillators are not used in modern equipment. Therefore the amplifier klystron is emphasized in this article. The klystron was invented in 1938 by the Varian brothers (1,2) to utilize the finite transit time of electrons in motion (which is a severe impediment to the operation of most electron devices at microwave frequencies) and thereby obtain previously impossible levels of microwave power. The klystron is called a linear beam device, since the fields that influence the electron motion are predominantly in the same direction as the electron motion. As the frequency is raised for all electron devices, the transit time of the electrons eventually causes low efficiency and poor operation. The basic idea is to start with an unbunched, moderate velocity electron beam in a magnetic system such that the beam translates along an axis with minimal radial spreading. If two RF cavities are also along this axis, the first one can be driven by an external RF source (the input cavity), and the second can serve as a source (the output cavity) of microwave power. This power is obtained from the kinetic energy of the electron beam, which comes from the dc power supply. Figure 1 shows a simplified drawing of a four-cavity klystron. If we arrange the various cavity voltages and phases such that the beam is converted in tight bunches that cross the output gap periodically, we would expect to convert a significant portion of the electron beam energy into microwaves. Tuning the intermediate cavities to frequencies above the operating frequency makes the induced voltage and phase correct to maximize the bunching.

The principle of operation is called velocity modulation. The electrons are emitted in a continuous stream at the cathode, and accelerated to a moderate velocity by the dc fields in the electron gun. We want the electrons to arrive at the output gap in short bunches, so these bunches can be slowed down by the fields in the output cavity. In this manner, energy from the power supply is converted into microwave energy in the output cavity. In a gridded vacuum tube, the control grid is used to convert a continuous stream of electrons from a cathode into bunches, but the grid only works well when the time the electrons take to move from the cathode to the grid is small compared to an RF period. The input cavity in the klystron has an RF voltage that makes a field that oscillates with time along the axis. The klystron is designed so that the first electrons in each period are slowed down, and the last electrons in each period are accelerated, while the electrons near the center of the period are left alone (the *E* field is a cosine wave, in this example). As the initially uniform density beam drifts down the axis, the faster electrons at the rear catch up to the slower electrons from the front, and, if the dimensions are correct, the fast, slow, and average

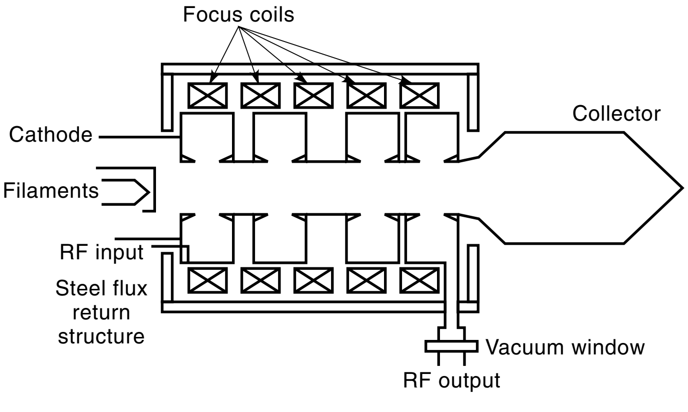

Figure 1. Simplified sketch of a four-cavity klystron. The klystron body is at ground potential, and a high voltage, negative polarity power supply is attached to the cathode.

velocity electrons arrive at the output gap center at the same time. Of course, with a continuum of electrons in the bunches cavity, and in the presence of the unavoidable electron repulsion (space-charge) effects, the bunched beam is only more temporally concentrated in the output cavity, and the electrons remain distributed in time. Thus, the beam is density modulated at the output gap, and a careful analysis (see below) shows that the velocity and density modulation are cosine and sine waves, respectively.

Several of the reasons for the klystron's importance in rf power generation may be seen from Fig. 1. The major advantage is that the klystron is naturally made of three main components: the electron gun (on the left), the RF interaction section, and the collector, on the right. Each component has only a simple function, and can be designed almost independently of the other parts. Thus, there are essentially no rf fields in the electron gun region, so it is designed to make a good, laminar, and uniform electron beam. Similarly, the RF section is comprised of several resonant cavities that are designed to optimize the gain and efficiency of power conversion. Significant heat is developed in the collector area, and this can be designed to safely dissipate large amounts of heat, since there are no dc and only minimal RF fields in this region. When power is expensive, the heat in the collector may be reduced by designing a multiple-stage depressed collector, so that the fields in the collector sort the electrons in the spent beam, and the beam is collected at several potentials, thereby reducing the heat produced and the power consumed. There are mechanical problems introduced by the complexity of the multiple-stage depressed collector, and the power supply becomes more complicated, so this technique is only used where power is expensive, such as satellite and airborne applications. Depressed collectors are also used in UHF television transmitters, where the electrical power costs can be a significant portion of the annual operating costs, since these transmitters operate for 24 hours per day with peak output powers at or above 50 kW.

APPLICATIONS OF THE KLYSTRON

The major uses of the klystron are in UHF television transmitters, particle accelerators, communications systems uplinks, and radar. There are several thousand UHF television transmitters in the world, and a majority of the higher power ones, above 50 kW, use the klystron as the final amplifier. The more modern UHF television transmitters use either klystrodes or depressed-collector klystrons to save energy. The latter are discussed subsequently. The most common particle accelerator is the electron linear accelerator, and about five thousand are used for tumor treatment and medical diagnoses in the world. About half of the newer, higher power medical accelerators are driven by klystrons, while the lower powered half are driven by magnetron oscillators. Particle accelerators for nuclear science are generally powered by klystrons, and a review is given in Ref. 3. Indeed, the modern, high-power klystron (4) was developed to power the Stanford Linear Accelerator, which is the world's highest energy electron accelerator. The development of the high-power klystron started at Stanford after Word War II, and the power levels of pulsed klystrons were increased from 30 kW to over 50 MW over a few decades. The linear particle accelerators for nuclear physics are usually even more powerful than the medical accelerators, and klystrons are the most popular vacuum devices used for these applications. This is especially true for large, high-power accelerators. The largest linear electron accelerator is the Stanford Linear Accelerator, and it uses 320 of the 50 MW peak power klystrons at 2856 MHz and 3 μs pulses at repetition rates as high as 360 Hz. The highest powered proton linear accelerator is at the Los Alamos Neutron Science Center, where 44 of the 1.25 MW peak klystrons operate at 805 MHz with 1 ms pulses at a 120 Hz repetition rate.

The role of the klystron in radar is diminishing, since the klystron is best suited for large, high-power transmitters. However, the air-traffic control system use klystrons in airport radar, and klystrons are also used in weather radar. Thus, there are over 2000 radar klystrons in operation, but many radar applications now use many small amplifiers, whose phase can be controlled to electronically steer the radar beam. This combination can still give moderate to large output powers, and the steering can be done electronically, so it is very rapid.

Another market is the satellite up-link transmitters, whose numbers are about 7000. Most of these have klystron amplifiers, but some of the newer ones use traveling wave amplifiers as their final amplifier. The traveling-wave amplifier has a greater bandwidth, and it can be smaller, so it is becoming the amplifier of choice for this application.

DESIGN METHODS

The design methods depend on the klystron component, corresponding to the labels in Fig. 1. Each section of the klystron may be designed almost independently of the other sections, which simplifies the design and optimization processes.

Electron Gun

The first section is the electron gun, and its design is a dc problem, complicated by large space-charge fields. The cathode is space charge limited, so the emission follows a Child–Langmuir law, with the current proportional to the 1.5th power of the cathode to anode voltage, and the proportionality constant is called the perveance, P. Thus, the cathode current is given by the expression

$$I = PV_{\mathrm{A}}^{3/2} \tag{1}$$

where V_{A} is the anode voltage. The modern electron gun was invented by J. R. Pierce (5), but his methods provide only a starting point for the design. A good electron gun has laminar (noncrossing) trajectories, and a relatively uniform cathode current density. The gun must also have the correct current at the design voltage, and the electric fields in the gun must be low enough so that sparking very rarely occurs. The peak and average current density at the cathode must be low enough so the cathode life is satisfactory (see CATHODES for more details). The detailed design of the electron gun is accomplished with Poisson equation solvers that solve Poisson's equation for the electric (and magnetic) static fields, and the Lorentz force equations with finite-element or finite difference methods. Three dimensional computations are sometimes required to account for grids or other nonsymmetric features. Another constraint on the gun design is that the beam radius at the entrance to the RF interaction region must be small relative to the operating wavelength. For good performance, the normalized radius of the beam, $k_r b$, must be in the range of 0.5 to 1.0, where b is the beam radius at the entrance to the RF region, and the radial propagation constant is

$$k_r = \frac{\omega}{u_0 \gamma_0} \tag{2}$$

where ω is the radian frequency of operation, γ_0 is the relativistic mass ratio for the electron, and u_0 is the velocity of the electron beam corresponding to the average beam voltage, V_0. For low beam currents, the average beam voltage is the anode voltage, but the space charge fields of the beam at higher currents reduce the beam's kinetic energy. The mass ratio is essentially unity for low beam voltages, and in general, is given by

$$\gamma_0 = 1 + \frac{\eta V_0}{c^2} \tag{3}$$

where c is the velocity of light, and η is the magnitude of the electronic charge to mass ratio. If we assume that the charge density in the beam is constant, we can use Gauss's Law to show that the voltage at the beam center, V_c is

$$V_A - V_c = \frac{I}{2\pi\epsilon_0 u_0}\left(\frac{1}{2} - \ln(b/a)\right) \tag{4}$$

where a is the radius of the beam tunnel, and ϵ_0 is the permittivity of free space.

The simplest klystron electron gun produces a solid cylindrical beam, with the cathode at a negative voltage and the anode at ground potential. This design is best for short pulse applications, where the high-voltage pulse comes from a pulse transformer. An advantage of this design is that the gun is as simple as possible: it is a diode. This simplicity has two advantages: first the parts count is minimum, and this helps cost and reliability, and secondly, the fields in the gun region can be minimized for any given peak output power with this design. The second type of electron gun has a modulating anode, and both types are shown in Fig. 2. This electron gun may be called a *triode type,* since there is now a second anode and a second insulator in the gun. In operation, voltage of the modulating anode controls the beam current. The modulating anode is a complication in the design, and it is used either for long pulse applications for pulses above 0.5 ms (where the pulse transformer becomes very large), or for high-efficiency operation, where the beam current is adjusted to optimize the efficiency for a given operating cathode voltage and output power. The modulation anode becomes the anode of the gun, and the voltage between the modulating anode and the anode forms a lens that must be accounted for in the design. The modulating anode aperture is made thick enough so that when it is at the cathode potential, only negligible current flows in the klystron. The cathode is usually shaped to be a segment of a sphere for a solid beam, but it can have a conical shape to produce a hollow beam. This is the magnetron-injection gun, and it also is shown in Fig. 2. Hollow-beam klystrons have some advantages, including higher perveance and potentially higher efficiency, but the magnetron-injection gun can be noisy, since the electrons circulate around the cathode, and influence the emission.

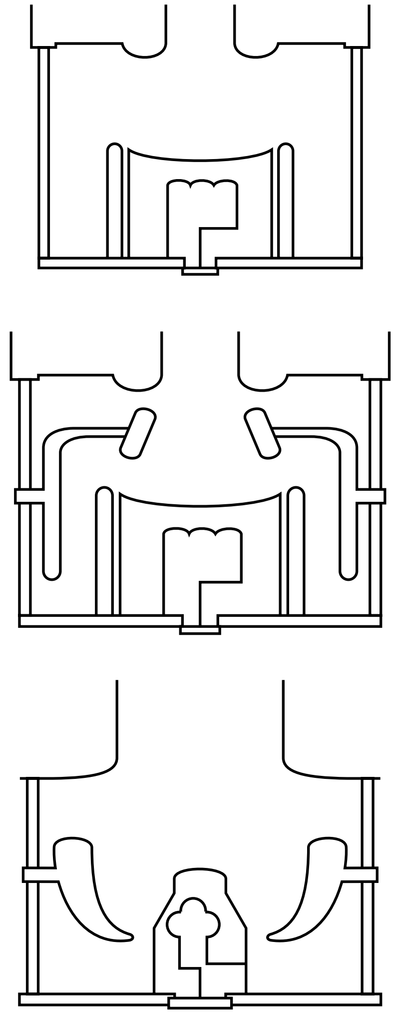

Figure 2. The three types of klystron electron guns: right, the diode gun; center, the modulating-anode gun; left, the magnetron-injection gun. The high-voltage insulators are shown shaded.

RF Cavities

The RF cavities must be designed for a high R/Q ratio (which is a measure of the efficiency of the interaction compared to the stored energy in the cavity), good coupling to the beam, and the correct resonant and harmonic frequencies. The input and output cavities are generally tuned close to the operating frequency, and the remaining cavities are tuned for the desired bandwidth and efficiency, as determined either by experiment, or by specially written, nonlinear, large-signal klystron software. Most of the intermediate cavities are tuned above the operation frequency to maximize efficiency, and the detuning increases towards the output cavity. The cavity shape is called reentrant, since this shape puts most of the electric fields in the beam region. Typical reentrant cavity shapes are shown in Fig. 1. The cavities are each designed for a particular frequency, but mechanical tuners are usually included to compensate for manufacturing tolerances. Some klystrons, especially those for UHF TV transmitters, are designed so the tuners may be adjusted by the final customer, to change the center frequency (TV channel) on demand. Another subtlety of the cavity design is that it is unwise to make the geometry too similar from cavity to cavity. If the cavities all have the same geometry, the higher order cavity modes are likely to overlap, and this increases the probability of exciting significant harmonic voltages with the harmonics of the beam current. The highest R/Q ratio is when the gap is centered in the cavity, but the gaps are often offset by varying amounts, which slightly reduces the R/Q ratio, but which also significantly alters the harmonic frequencies. Remember that the designer is trying to achieve perfect delta-function bunches of current, and thus the amplitude of all the harmonic currents may be up to twice the dc component. Thus, low impedance at the first few harmonics of the beam current is another requirement on the cavities. Low impedance at the higher harmonics is not important, since the coupling of the cavity fields to the beam is generally small for high harmonics.

The Magnetic Circuit

The magnetic circuit is designed to keep the beam confined. Most klystrons have an axial magnetic focusing field (supplied by either a solenoid or permanent magnets) that counteracts the radial repulsive force on the electron beam. A focus solenoid is shown schematically in Fig. 1. The focus coils and their return circuits can be heavy and rather expensive in a pulsed klystron, and the power dissipated in the focus coils can be several kilowatts. Research is under way to make short-pulsed, high-power klystrons with permanent magnetic focusing, to eliminate this loss of energy and the weight and expense of the focus coils and their power supplies. Permanent magnet systems are also used with either a single magnet or periodic focusing, and the reader should see TRAVELING WAVE TUBE for more information on periodic focusing systems. Permanent magnet focusing is used on several commercial medium power (up to 5 kW) klystrons in the 1.5 to 3 GHz frequency range.

At the gun end, the magnetic field is designed to be parallel with the electron trajectories, so the trajectories are unchanged by the field. The magnetic field balances the space charge forces, and the magnetic field required by the unbunched beam is given by the relation

$$\omega_c^2 = \frac{2\omega_p^2}{\gamma_0(1-K)} \tag{5}$$

where $\omega_c = \eta B_{z0}$ is the cyclotron frequency, B_{z0} is the axial magnetic field at the entrance to the RF interaction region, where the beam has a minimum diameter,

$$\omega_p = \sqrt{\frac{\eta\rho_0}{\epsilon_0}}$$

is the free-space plasma frequency, ρ_0 is the space charge density at the beam minimum, and K is the square of the ratio of the magnetic flux at the cathode to the magnetic flux at the beam minimum. The range of K is from 0 to 1, with $K = 0$ being called the Brillouin flow case, after its inventor, and K approaching 1 is the confined flow case, where the electrons follow lines of constant magnetic flux, and no radial motion is possible. The higher values of K make the beam more resistant to radial spreading, and are used at high frequencies. The Brillouin case is difficult to achieve, since flux lines from the focus magnet tend to link the cathode, but it can be achieved approximately with a bucking coil whose excitation is adjusted to null the magnetic field at the cathode surface. As the beam bunches, the radial space-charge forces grow, and the axial magnetic field increases by a factor of about two at its peak near the center of the output gap. The magnetic field then drops quickly to cause the beam to rapidly expand into the collector. With careful design, including use of Poisson-equation solvers, all these requirements can be realized with a single set of coils and magnetic pole pieces connected with a single power supply.

It is also possible to transport the electron beam through the klystron with an array of electrostatic lenses. Electrostatic focusing was investigated seriously for satellite transmitters when designers thought that the only solution for satellite broadcasting to earth was with 500 W to 1000 W transmitters on the satellite. Several prototype, light-weight, electrostatic-focused klystrons were designed and built, but improvements in the receiver noise figure rendered these higher powered transmitters obsolete before they were ever deployed in space.

Collector

The collector's function is to stop the beam and transfer the heat produced by this action to a cooling media. The most stressful operation for the collector is the case with no RF signal applied to the klystron. In this case, the entire beam power is dissipated in the collector. In its basic form, the collector is a hollow cylinder terminated in a cone, that is part of the overall vacuum envelope. The exterior has a cooling jacket, generally with water as the coolant, and lead shielding is used with the higher powered klystrons, since the electrons produce X rays when they are suddenly stopped. The maximum power density must be limited to 500 to 1000 W/cm^2, depending on the cooling method, with the former applying to turbulent flow cooling, and the latter for mixed phase water cooling, where steam is generated at the outside of the collector, but rapidly condenses in the cooling stream. Copper, because of its high thermal conductivity, is the most common collector material, but key parts of the collector are often made of stainless steel, to strengthen the assembly.

For pulsed klystrons, it is desirable to have the collector capable of being isolated from the rest of the klystron with a ceramic joint. This allows the precise monitoring of the body current, and the body current may be monitored to protect the klystron. Many klystrons dissipate from 3% to 10% of the beam power in the body, and this component is not usually designed to dissipate much power.

The Depressed Collector

Only the kinetic energy of the moving electrons can be converted into microwave energy. After the beam has gone through the output gap, its remaining energy is converted into heat when the electrons strike the collector surface. However, a majority of this energy may be recovered by designing an array of electrodes at carefully selected potentials to form the collector. This is called a multistage depressed collector, and it is used in space-borne and television transmitters to reduce the energy demands on the power supply. A schematic

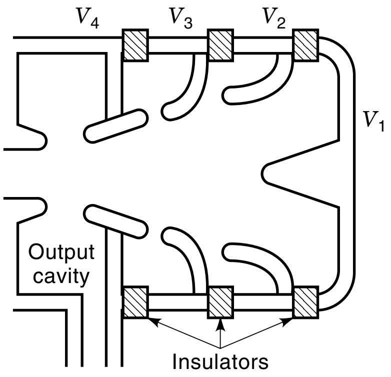

Figure 3. Schematic diagram of a depressed collector with four potentials.

of a depressed collector is shown in Fig. 3. The voltages on the figure follow the inequality $V_c < V_1 < V_2 < V_3 < V_4$, where V_c is the cathode voltage. In practice, V_4 may be only a few percent of the cathode voltage, thus, when no signal is applied to the klystron, all the current is collected on the lowest collector, and the power supply only has to provide a few percent of the normal beam power. The electrostatic fields in the collector region sort out the electrons by their kinetic energy. Consider a case with three energy levels in the spent beam. The electrons with the most energy are intercepted at potential that is close to the cathode, while the electrons with a lower kinetic energy are intercepted at a potential that is between the cathode and the anode, and those with the lowest kinetic energy are intercepted at the anode potential. The kinetic energy of the high-energy electron classes is reduced by the work done moving to a more negative potential, so the heat produced at the collector is reduced, as is the power from the power supply. In this example klystron, the power supply must produce three more voltages, in between the cathode and anode potential, so the power supply is more complicated. However, when energy must be conserved, the depressed collector can save energy. The energy that can be recovered by the depressed collector increases with the number of stages, or potentials, in the collector, but so does the complexity of the power supply.

There are three practical problems of the depressed collector that should be addressed. First, the collector segments must have a low secondary emission ratio, since secondary electron current will travel to a higher potential, and absorb energy from the power supply. Second, the electrons should all hit the collector segments where the electric field will push any secondary electrons back into the emitting electrode. Third, the insulators and cooling system must be carefully designed, so only acceptably small amounts of RF radiation are emitted into the space surrounding the collector. The beam in the collector is partially bunched, and it can deliver real RF power to the collector and its circuitry.

High-power (above 50 kW), high-efficiency klystrons have not been produced with depressed collectors, since in this type of klystron, some electrons are almost stopped in the output gap, so if there is a potential barrier in the collector, these very slow electrons can be returned to the RF interaction region, and cause the klystron to be unstable. However, depressed collector klystrons are commercially available for the UHF television band at the 50 kW level.

Mechanical Considerations

The major mechanical requirements are that the klystron have a good vacuum, be strong enough to withstand the stresses of handling and from the water system, and the mechanical design must be repairable. The klystron must also withstand the thermal stresses involved in normal operation and during the bakeout process, which is a 450° to 600°C bake for two to three days for a large klystron. To allow repairs, the klystron often has weld flanges between cavities and at the collector and electron gun. The design must also have no trapped volumes, so it can be out-gassed during the bakeout. Materials consistent with high vacuum must also be used, such as oxygen-free, high-conductivity copper, stainless steel, and tungsten and tantalum in the gun area. The RF window is generally made of high-purity aluminum or beryllium oxides, both of which have low losses, and which can be brazed to thin metal membranes for attachment to the klystron.

LIMITATIONS OF THE KLYSTRON

Efficiency

The maximum efficiency obtainable with a klystron remains an open question. For decades, the 58% result mentioned previously was considered the maximum theoretical limit, but numerical calculations involving second harmonic cavities, first published by Lien (6), showed that 70% to 75% efficiencies may be obtainable. The early experimental results (7,8) showed that the new numerical results were essentially correct, but it was several years before the first commercial klystron with over 60% efficiency was produced. The maximum efficiency achieved to date is 76%, in an S-band, 100 kW CW klystron (9) designed for industrial heating. However, for the highest efficiencies, the klystron's bandwidth, gain, and even stability are reduced, due to electrons that are returned from the output gap. Most of the high-efficiency klystrons have a second-harmonic cavity to optimize the shape of the bunch, and the S-band record klystron referred to previously has two second-harmonic cavities. Unfortunately, space-charge effects reduce the klystron efficiency, so for high efficiency, the klystron must be designed with low beam current, and low perveance, P, which is a geometrical factor of the electron gun. Based on results of large signal calculations and on experimental data, the optimized efficiency of klystron is estimated as (10)

$$\eta_e = 0.82 - 0.228P \cdot 10^6 \quad (6)$$

Thus, it is plausible that 80% efficiencies may be available in the future, provided that the market is large enough to support the necessary research. There will likely be more than one harmonic cavity in 80% efficient klystron. Equation (6) is an expression for the electronic efficiency which neglects the losses in the output cavity, which are also a function of the perveance or the operating voltage. While these losses are usually small, for very low perveance they become proportionately larger, and cannot be neglected.

Power

The maximum power that may be obtained from the klystron is limited by arcing considerations in the region of the electron gun, the output cavity, or the output window. At the highest peak powers, there is an inverse correlation between maximum peak output power and pulse length, since both pulse-voltage and rf-breakdown depend on pulse width. In the sub-microsecond region, klystrons have been made with field-emission cathodes and up to 15 GW (11) output powers. For pulse lengths of a few microseconds, the peak power is limited to about 150 MW (12). In the CW regime, the record peak power is 1.3 MW (13), and only slow progress has been made in raising this power from the first practical 1 MW CW klystron 10 years ago. The effect of pulse length on the peak power obtainable from a given klystron often varies as the pulse length to the $-1/2$th power. Representative state-of-the-art peak powers are 150 MW for 3 μs, 20 MW for 15 μs, and 5 MW for 1000 μs. This is typical of short and medium pulsed klystrons.

For the highest peak powers, the output cavity electric fields must be minimized. The first step to reduce these fields is to round the cavity noses more, but this also reduces the interaction impedance. Major improvements in the output fields are obtained by separating the output cavity into two or more coupled cavities, separated by a short drift space. With two cavities, for example, the voltage of each cavity is reduced to 50% of the single cavity value, and so the fields are reduced also by this same 50%. The ohmic losses in the output cavity are proportional to the square of the cavity voltage, so the losses for the two-cavity system will each be only be 25% of the original single cavity, and the total ohmic losses will be 50% for the two-cavity system compared to the single cavity solution.

Frequency

The beam dynamics allow frequency scaling in the klystron, so that if all the dimensions are changes by a factor, k', the klystron will operate with the same characteristics at a new frequency, f/k'. However, if k' is less than unity, all the current and power densities in the new klystron will be $1/k'^2$ as high, so this limits the power available at high frequency. Both peak and average power then scale as f^{-2}. Hence, the optimum frequency range for the klystron is from 0.5 to perhaps 20 GHz. Reduced power klystrons are available at up to 100 GHz. The low frequency limit occurs because of the massive size of a low-frequency klystron. With solid beams of ordinary perveance (between 0.75 and 2.0×10^{-6}) the low frequency limit is about 200 MHz. Hollow or multiple beams may permit a reduction in this lower limit, since with higher currents we have a slower electron velocity and therefore a smaller klystron.

The extended interaction klystron uses a set of coupled cavities to replace each cavity in the klystron. Amplifiers can be made with the extended interaction technique at frequencies up to 100 GHz. For even high-frequency operation, the gyroresonant principle must be used, and the gyroklystron is discussed further in the gyrotron section.

Bandwidth

The bandwidth of the klystron is relatively small, since there are five or more tuned cavities in the klystron. The loaded Q's of these cavities depend on their shape, the frequency, and the beam current, since the beam loading is the most important factor in determining the cavity loading. The designer has very little control over these variables: the shape is always reentrant, with a gap that does not exceed one radian: the frequency is set by the application, so only the beam current can be controlled. The beam current follows Eq. (1). The output power P_o depends on the electronic efficiency and the power in the klystron beam, $P_o = \eta_e P V_A^{5/2}$. Since the beam loading is proportional to I, one achieves high bandwidth by increasing the beam current, for a given power, but this reduces the overall efficiency. In practice, klystrons with high (above 65%) efficiency tend to have 1 dB bandwidths of about ±1%, and if the perveance is increased, the efficiency drops to under 50%, but the 1 dB bandwidth can be increased to 15% (14), even for klystrons at the 1 MW power level. Large bandwidths are easier to obtain in the klystron with high-output powers, since the beam impedance decreases as the operating voltage increases. The dc beam resistance is given by the relation, $R_o = 1/(PP_o^{0.2})$, and this is proportional to the maximum fractional bandwidth. Thus, wideband klystrons must either have high perveance, or high output power. Up to 10 cavities may be used, and optimally tuned to increase the bandwidth, and multiple resonances are designed into the output cavity and its coupling system. The klystron is not suited for wide-band low-power applications, and the bandwidth, even for high-power devices, is limited to 15% to 20%. The cluster-cavity concept (15), where each cavity is replaced by a set of closely spaced cavities, has the potential to make improvements in both bandwidth and efficiency, and devices with up to 25% bandwidth should be possible with this concept. A wide-band, cluster-cavity klystron would have as many as 15 cavities, and it would be more expensive than a conventional klystron, but the bandwidth could be significantly greater.

Gain

The klystron generally has a gain of 40 dB to 60 dB, with the lower gain corresponding to either a few cavities or wide bandwidth. In narrow band applications, gains over 60 dB are possible, but the stability may suffer. At the higher frequencies, above 10 GHz, gain is more difficult to achieve, since the coupling function to the gap is not favorable.

Noise

The major noise sources in the klystron are (1) shot noise from the electron beam, (2) resistor noise from the input circuit, and (3) noise from the cathode temperature. The shot noise in a diode is given by the relation

$$\langle i_{\mathrm{n}}^2 \rangle = 2eIBF(\theta) \tag{7}$$

where e is the electronic charge, B is the klystron bandwidth, and

$$F(\theta) = \frac{4}{\theta}[\theta^2 + 2(1 - \cos\theta - \theta\sin\theta)] \tag{8}$$

and the transit angle of the diode is

$$\theta = \frac{2\omega L_{\mathrm{d}}}{u_0} \tag{9}$$

where L_d is the distance from the diode cathode to the anode. This value of the rms noise in the current is reduced by space charge effects, but the noise is proportional to the klystron current. Hence, high-power klystrons often have relatively high noise, with a noise figure of 30 dB being typical. When the klystron is used as a low-noise amplifier, it must be operated at low beam current. Even with low beam current, the klystron typically has a 6 dB noise figure, which is much higher than the few tenths of a dB that is possible with a good solid-state amplifier.

KLYSTRON VARIATIONS

Several physical variations of the conventional, solid cylindrical beam klystron have been studied, including the sheet beam (16), hollow beam (17), and the multiple beam (18) klystron. The cluster klystron (19) is a variation of the multiple beam klystron for very high output power where several beams are put in the same vacuum envelope but they feed a common output cavity. These designs spread out the beam to reduce the adverse effects of space charge. Both the hollow beam and multiple beam klystron have been demonstrated, but the latter is under active development and is discussed here. The fundamental concepts include: all klystron cavity gaps have a radial variation of the electric fields, so it is better to have all the electrons at one radius; and by spreading out the electron beam, the potential depression formed by the space charge will be minimized, so the variation in kinetic energy in the beam is minimized. In the interaction with the output gap, only the beam's kinetic energy can be converted to microwave power, the potential energy can only be recovered by using a multiple-stage depressed collector (20), which reduces the energy of the collected electrons. This in turn, reduces the power from the power supply, but does not increase the output power of the klystron.

Another variant of the klystron is a hybrid of the traveling-wave amplifier (used as the input section) and the klystron output section (or vice-versa). This type of amplifier can easily achieve 10% to 15% bandwidth, high output power, and good gain. The extended-interaction klystron has an RF structure that consists of several coupled cavities, rather than single cavities. With this technology, monotron oscillators can be built to produce 1 kW at frequencies up to 325 GHz, and amplifiers can be made up to 100 GHz.

Relativistic Klystron

Since the electron has a rest mass of 511 keV, relativistic effects start to appear at only 50 kV, so most high-power klystrons have relativistic effects in their detailed design. However, the term relativistic klystron is only applied to those klystrons operating at or above 500 kV, where relativistic effects are extremely important. The relativistic factor for klystron scaling with voltage is $\gamma_0^{3/2}$, so for a given frequency, the length becomes very long for high-voltage operation, or for γ significantly larger than unity. Thus, the relativistic klystrons often exploit a *gating effect* of an electron beam that is very near the space-charge propagation limit. The propagation limit occurs when the potential depression due to the beam's space charge is so high that all the kinetic energy is converted into potential energy, and the beam stops. This limiting current depends on the geometry of the beam and the surrounding drift tunnel or cavity. The limiting current for a solid beam of radius b in a drift tunnel of radius a is (21)

$$I_{\max} = \frac{4\pi\epsilon_0 mc^3}{e}\,\frac{(\gamma_0^{2/3}-1)^{3/2}}{1+2\ln(a/b)} \tag{10}$$

where m is the rest mass of the electron and the first ratio on the right-hand side is called the Alfven current, which is 17.1 kA for electrons.

The beam current in the relativistic klystron is generally a few tenths of this limiting current, while for conventional klystrons the current is often less than one tenth of the limiting current, but it increases with beam voltage. By operating fairly close to the current limit and carefully controlling the transverse geometry, the bunching distances for the relativistic klystron may be drastically reduced from the classic formulas given later, which do not include the gating effect. To obtain such high current, the relativistic klystrons often utilize field emission cathodes, which limits their performance to pulse lengths below 1 μs and limits the repetition rate for the pulse per minute range. The formidable output power of around a gigawatt can be produced, but the efficiency is generally only 20%, because the beam motion during the short pulse is not as uniform and laminar as is possible with lower current beams.

Many variations of the relativistic klystron are possible, and some of the most successful to date have been the virtual cathode or vircator family of devices (22).

Reflex Klystron

The reflex klystron has a reflector electrode after the first cavity, so the electrons pass through the cavity, are reflected by the electrostatic field from the reflector, and traverse the cavity again in the reverse direction. The beam is velocity modulated by the cavity in the first pass, and the beam will be bunched in $n + 3/4$ RF periods, where n is any positive integer, including zero. By varying the potential of the reflector, we can adjust the time the electrons spend in the reflector region, and this changes the frequency of the oscillator. Hence, the device is inherently electronically tunable, so it has been applied primarily as a local oscillator, at the milliwatt power levels. High output powers are possible, but the device has lower efficiency than the conventional klystron, since the bunch geometry cannot be optimized in the reflex case.

Monotron Oscillator

The monotron is another single cavity oscillator. The fundamental principle is that the impedance that the unbunched beam presents to a cavity is negative for long transit angles, and the magnitude of this negative impedance varies linearly with the beam current. Hence, if the cavity and beam are properly designed, the real part of the cavity impedance can be negative and the cavity will oscillate, extracting power from the beam. One of the pitfalls of klystron design is that a cavity, or more often, an inadvertent resonator in the electron gun region, may start to oscillate at the klystron's design current, due to a monotron oscillation. The designer must know the impedance seen by the beam as a function of frequency, and remove the oscillation possibilities by reducing the Q of the unwanted peaks. This is especially important for high-current beams.

THEORY

There are two different limiting small-signal theories of the klystron that are each valid in their own small-signal regions. But the klystron is a very nonlinear device, and one must resort to numerical calculations to predict the efficiency, large-signal gain, and the phase and amplitude transfer functions of the klystron.

Small-Signal Theory

There are two simple theories of klystron operation, Webster's ballistic theory (23) and the space-charge wave theory (24). The ballistic theory is valid in the limit of small space-charge forces. The principal result of the theory, when applied to a two cavity klystron, is that the nth harmonic current amplitude is

$$\left|\frac{i_n}{I_o}\right| = 2J_n\left(n\frac{\alpha M\theta_d}{2}\right) \tag{11}$$

where I_o is the dc beam current, J_n is the nth order Bessel function, α is the ratio of the voltage at the input gap to the dc beam voltage (V_o), M is the gap-coupling coefficient, a number less than 1 that expresses the efficiency of the RF fields in the input gap in coupling to the beam, and $\theta_d = \omega L/u_o$ is the drift distance (in radians of transit time) between the center of the input and output cavities. For the highly idealized case of a gridded planar gap, $M = [\sin(L_\mathrm{g}/2)]/[L_\mathrm{g}/2]$, where L_g is the distance between the grids, measured in radians. If we assume an output gap with its value of M and α, then the electronic efficiency (the ratio of the RF energy produced to the beam's kinetic energy) may be written as

$$\eta_e = M_2\alpha_2 J_1\left(\frac{\alpha M\theta}{2}\right) \tag{12}$$

where the subscript 2 refers to the output cavity. When $M_2\alpha_2 = 1$, the effective gap voltage experienced by an electron equals the dc beam voltage, and electrons will begin to be reflected from the output gap, and this can cause instabilities due to the electronic feedback. The first maximum of $J1$ is approximately 0.584. Thus, the limiting value of klystron efficiency is half the current bunching ratio, or 58%. For several decades after the invention of the klystron, no klystron produced 58% efficiency, but the modern klystron can have an efficiency of up to 76%, and even higher with development.

The bandwidth and frequency response of the klystron was first calculated with the space-charge wave theory. The space-charge wave theory of the klystron is valid when the gap voltages are small, and space-charge forces are high. The bunching in the klystron can be explained as a result of two waves carried by the electron beam, a current wave and a velocity wave. These waves obey a transmission line equation, and are sinusoidal with distance and time for the usual case of an unaccelerated beam (25). The voltage at the input gap modulates the velocity of the electrons as they cross the gap (and thus initiates a current wave), and in the drift space the velocity modulation is converted to current modulation. These modulation waves are a result of longitudinal plasma oscillations of the electrons, but it is complicated because the magnetic field and boundary conditions in the drift tubes also affect this plasma frequency. The result of this theory is that each cavity gap in the klystron excites a current and a velocity wave on the beam. The first cavity is driven by an external source (the drive signal), which excites a current wave plus a small velocity wave, due to the finite axial extent of the gap fields. The current wave is a sine wave with distance, so it grows. This wave interacts with the second cavity impedance and produces a larger voltage in the second cavity compared to the input cavity, provided that the second cavity is tuned reasonably close to resonance. This cavity voltage excites a second current and velocity wave, which adds to the original waves from the first cavity, and the process is repeated at each cavity. If we neglect the small velocity waves and concentrate on the current waves, then the standing waves set up by an input gap are of the form (26)

$$\frac{u_1}{u_0} = \frac{\alpha M}{2}\cos Z_1 \tag{13}$$

and

$$\frac{i_1}{I_o} = -j\frac{\alpha M}{2\omega_p/\omega}\sin Z_1 \tag{14}$$

where $Z_1 = (R\omega_p z)/(u_0)$ is the axial distance measured in reduced plasma radians. The plasma reduction factor R is a measure of the reduction in the plasma frequency by the combined effects of the drift tunnel and the magnetic focus field. The plasma frequency is the free-space oscillation of electron density variations, for a one-dimensional situations. In the klystron, the space charge fields are two-dimensional, and a significant fraction of the space-charge electric fields terminate on the drift tunnel walls, rather than on electron scarcity regions. The net result is that the actual plasma frequency, $\omega_q = R\omega_p$, is usually about one-tenth of the free space value. The value of ω_p/ω is almost always less that unity, and this ratio usually is a few times 0.1. Thus, the current wave is generally from 3 to 10 times larger than the velocity wave, which is often neglected. The small-signal bandwidth of the klystron may be determined by calculating the waves that begin at each cavity, due to the voltage produced in that cavity by the prior cavities. However, the electron beam itself loads down each cavity with a capacitive and a resistive component that are in parallel with the usual L, C, and R parallel elements that represent the cavity at the detuned short plane. If the gaps were gridded, the conductance $G = G_b + jB_b$ supplied by the beam to the gap is calculated from the subsequent relations.

$$\frac{G_b}{G_o} = 1 - \frac{\cos L_\mathrm{g}}{L_\mathrm{g}^2} - \frac{\sin L_\mathrm{g}}{2L_\mathrm{g}} \tag{15}$$

and

$$\frac{B_b}{G_o} = \frac{\sin L_\mathrm{g}}{L_\mathrm{g}^2} - 1 + \frac{\cos L_\mathrm{g}}{2L_\mathrm{g}} \tag{16}$$

where G_o is I_o/V_o, the dc beam conductance. These small-signal equations are easily programmed on small computers, and are widely used to estimate the bandwidth of klystron designs. Note that when designing a wide-band klystron, there are frequencies at which the response from the current waves discussed previously is very small. The total response is the sum of the responses from the current waves and from the small velocity waves that have been neglected. Under these conditions, the velocity waves cannot be neglected.

Large-Signal Simulation

Since the klystron is such a nonlinear device, with many parameters, the linear theories cannot be used to predict the overall efficiency or the power that is intercepted along the klystron body, and large-signal nonlinear computer programs must be used to optimize the efficiency. The first large-signal klystron analysis was performed by Webber in 1958 (27). For the next decade, the early klystron simulations were not very accurate, with about 10% to 15% errors, since the theory was not self-consistent. The force equations were written for both gap and drift regions, with approximate expressions for the space charge. Electrons were tracked through a series of cavities and drift regions, but the amplitudes and phases of the gap fields were estimated by circuit equations that basically came from the linear space-charge wave theory, where the beam current is assumed to be unaffected by the cavity fields. These amplitudes and phases were not necessarily correct, since the beam's current at large gap fields is altered by the gap fields. The necessity of iterating this procedure was first published by Kageyama et al. in 1977 (28). The older methods were still used to estimate the voltages and fields in each cavity, but in addition, for each cavity, the induced current is calculated from Ramo's induced current theorem (29), which states the equivalence of the electrical energy change in a circuit to the work done by the particles on fields. For the klystron, the general form of the induced current is

$$i_i(t) = \frac{\int_V J(t) \cdot E(t)\, dV}{V_g(t)} \tag{17}$$

where the space-charge current is given by J, the electric field E is only that due to the cavity, V_g is the gap voltage, and V is the entire volume over which there are cavity fields. One next takes a Fourier component of this time function to get the appropriate frequency component of the induced current.

Once the last electron leaves a particular gap, the induced current is finally known, and the gap voltage and phase are recalculated, using the Fourier component at the appropriate frequency. The old and new complex gap voltages are averaged, and used for the next iteration of the beam through this gap. After a few such cycles, the new fields and phase are very close to the previous estimates, and the cavity parameters are then established. Then, the next drift space calculation is performed, and the process continues in the next gap, until the output gap is reached. The output gap is special because the output gap voltage is often greater than the beam voltage, and the optimum loading of the cavity is not known a priori. The difference between the beam current at the entrance to the cavity and the inducted current in the output cavity is very large, since the output cavity voltage is so great. The optimum coupling between the output cavity and the external load must also be found empirically (with a large-signal computer program), by varying the Q of the output cavity. The output cavity is a parallel RLC circuit, (when viewed from the waveguide plane of the detuned short), and the beam is a current source, while the load being drives by the klystron is coupled to the output cavity by an iris, or a loop at low frequencies. This coupling iris can be represented by a transformer. The schematic is shown in Fig. 4. For the simple case where the load is purely resistive, the coupling iris may be ignored, and the combination of the iris and the load resistor can be replaced by a resistor transformed to the primary of the transformer, which is then in parallel with the RLC circuit. Refinements of the method include using a wave equation solver to obtain accurate calculations of the cavity field distributions, and iterating over more than one cavity at a time when there are reflected electrons. These calculations must be repeated for each drive level, load on the klystron, and frequency, and so they are time consuming for large-bandwidth klystrons.

One of the most difficult calculations of the large-signal klystron programs is the evaluation of the space-charge forces. There are basically two methods for calculating these forces. The earliest method is to calculate the Green's function for the charged particle being followed, while accounting for the particular boundary conditions. For example, the Green's function fields at the point r,z for a unit-charged ring of radius r' and position z', moving with velocity u_o along the z axis, and contained in a conductive cylinder of radius a are (30)

$$E_r(r,z;r',z') = \frac{\gamma_o}{2\pi\epsilon_o a^2} \sum_{l=1}^{\infty} \frac{J(v_l r) J_o(v_l r')}{J_1^2(v_l a)} e^{(-v_l \gamma_o |z-z'|)} \tag{18a}$$

$$E_z(r,z;r',z') = \frac{\operatorname{sgn}(z-z')}{2\pi\epsilon_o a^2} \sum_{l=1}^{\infty} \frac{J_o(v_l r) J_o(v_l r')}{J_1^2(v_l a)} e^{(-v_l \gamma_o |z-z'|)} \tag{18b}$$

and

$$B_\theta(r,z;r'z') = \frac{u_o}{c^2} E_r(r,z;r'z') \tag{18c}$$

where the eigenvalues are the roots of $J_o(v_l a) = 0$. A finite approximation to the infinite series is only calculated once, at the start of each problem. There are two major difficulties with using these equations in a computer code. The first is that the space charge fields are added in a point-by-point manner, so the time spent calculating the fields grows with n, the number of particles, as n^2. This places a practical limit of around 100 to 300 particles with this method, for a personal computer. The other problem is more fundamental:

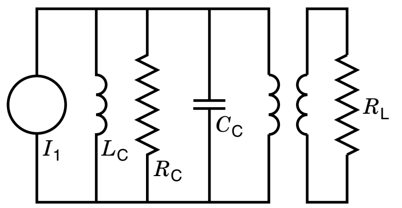

Figure 4. The equivalent circuit for the output cavity (the passive elements on the left of the transformer), the coupling transformer, the klystron's load impedance, and a modulated beam (the current generator) in this cavity.

these equations were derived by using a Lorentz transformation of the static fields of a moving charge into the laboratory frame. The γ_0 and u terms in the equations depend on this velocity. For most of the klystron, the particles move with an almost constant velocity, so this approximation is not bad, but in the penultimate and output cavities, there is a large spread of velocity, and Eqs. (18) lose their accuracy.

An alternative method of calculating the space charge fields is to directly integrate Maxwell's equations, with the bunched beam as a driving force. This method is called the particle-in-cell method, and a grid is set up over the klystron interaction area. The beam currents are averaged over the grid, and discretized versions of the curl equations are integrated to find the time derivatives of the fields. The major advantages of this method are that the method is valid for any distribution of particle velocity, and the computation time grows much more slowly, only as $n \log(n)$. A recent reference to the particle in cell method as applied to klystrons is Ref. 31, and a general reference to the particle in cell method is Ref. 32.

BIBLIOGRAPHY

1. R. H. Varian and S. F. Varian, A high-frequency oscillator and amplifier, *J. Appl. Phys.,* **10**: 321–327, 1939.
2. E. L. Ginzton, The $100 idea, *IEEE Spectrum,* **12** (2): 30–39, 1975.
3. P. B. Wilson, Development and advances in conventional high-power RF systems, *Proc. 1995 Particle Accelerator Conf.,* 1995, pp. 1483–1488.
4. M. Chodorow et al., Design and performance of a high-power pulsed klystron, *Proc. I.R.E.,* 1953, pp. 1584–1602.
5. J. R. Pierce, *Theory and Design of Electron Beams.* 2nd ed., New York: Van Norstrand, 1954.
6. E. Lien, High-efficiency klystron amplifier, *Proc. 8th Int. Microw. Opt. Generation Amplif. Conf.,* Amsterdam: 1970.
7. P. J. Tallerico, High performance klystrons for accelerator applications, *IEEE Trans. Nucl. Sci.,* **NS-18**: 257–259, 1971.
8. E. L. Lien, High efficiency klystron amplifier, *Paper 14.4, IEEE Int. Electron Devices Meet.,* Washington, 1969.
9. S. Arai et al., 2.45 GHz, 100 kW, high efficiency klystron, *Nippon Elect. Comp. J,* **46** (3): 145–149, 1993.
10. P. Tallerico et al., Techniques for maintaining design efficiency when operating klystron amplifiers at levels below the maximum output power, *IEEE Trans. Electron Dev.,* **ED-42**: 780–784, 1995.
11. M. Friedman and V. Serlin, Present and future developments of high power relativistic klystron amplifiers, *Proc. SPIE- Int. Soc. Opt. Eng.,* H. E. Brandt, (ed.), **1872**: 1992, pp. 2–7.
12. D. Sprehn, R. M. Phillips, and G. Caryotakis, Performance of a 150-MW S-band klystron, *Pulsed RF Sources for Linear Colliders,* **AIP Conf. Proc. 337**: 1994, pp. 43–49.
13. H. Frischholz, The LEP II RF power generation system, *Proc. of the 1993 Particle Accelerator Conf.,* Washington, 1993, pp. 1247–1249.
14. G. Faillon, G. Egloff, and C. Farvet, Very broad bandwidth klystron amplifiers, *Presented at the Colloque Inter. Sur le Radar,* Versailles, April 1989; A. Auberdiac, C. Bearzatto, and G. Faillon, A Wideband 3 MW peak S-band klystron, *1984 IEEE Inter. Electron Device Meet.,* 1984, pp. 656–658.
15. R. S. Symons and J. R. M. Vaughan, Linear theory of the cluster-cavity klystron, *IEEE Trans. Plasma Sci.,* **22**: 713–718, 1994.
16. K. Eppley, W. Herrmannsfeldt, and R. H. Miller, Design of a wiggler-focused, sheet beam, X-band klystron, *Proc. 1987 Particle Accelerator Conf.,* 1987, pp. 1809–1814.
17. E. K. Demmel, Some studies on a high-perveance hollow-beam klystron, *IEEE Trans. Electr. Dev.,* **ED-11**: 66–73, 1964.
18. E. A. Gelvich et al., The new generation of high-power multiple multiple-beam klystrons, *IEEE Trans. Microw. Theory Tech.,* **MTT-41**: 15–19, 1993.
19. R. B. Palmer et al., Status of the BLN-MIT-SLAC cluster klystron project, *Pulsed RF Sources Linear Colliders,* **AIP Conf. Proc. 337**: 1994, pp. 94–102.
20. R. S. Symons, Depressed collector klystrons for high-efficiency UHF television, *1982 Natl. Assoc. Broadcasters Conv.,* Dallas, 1982.
21. S. Humphries, Jr., *Charged Particle Beams,* New York: Wiley, 1990, p. 209.
22. V. L. Granatstein and I. Alexeff, *High-Power Microwave Sources,* Boston: Artech House, 1987, Chapters 13 and 14.
23. D. I. Webster, Cathode-ray bunching, *J. Appl. Phys.,* **10**: 501–508, 1939.
24. S. Ramo, Space charge and field waves on electron beams, *Phys. Rev.,* **56**: 276, 1939.
25. S. Bloom and R. W. Peter, Transmission-line analog of a modulated electron beam, *R.C.A. Review,* **15** (3): 95–112, 1954.
26. A. H. W. Beck, *Space-charge waves and slow electromagnetic waves,* New York: Pergamon, 1958.
27. S. E. Webber, Large-signal analysis of the multicavity klystron, *IRE Trans. Electr. Dev.,* **ED-5**: 306, 1958.
28. T. Kageyama, Y. Morizumi, and E. Watanabe, A large-signal analysis of broad-band klystrons and its design application, *IEEE Trans. Electr. Dev.,* **59** (1): 1976.
29. S. Ramo, Currents induced by electron motion, *Proc. IRE:* 584–585, 1939.
30. P. J. Tallerico and J. E. Rowe, Relativisitic effects in the traveling-wave amplifier, *IEEE Trans. Electr. Dev.,* 549–561, 1970.
31. B. E. Carlsten and P. Ferguson, Large-signal klystron calculations using KLSC, *Proc. 1997 Particle Accelerator Conf.,* Vancouver, Canada: 1997.
32. C. K. Birdsall and A. B. Langdon, *Plasma Physics via Computer Simulations,* New York: McGraw-Hill, 1985.

PAUL J. TALLERICO
Los Alamos National Laboratory