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POWER LIMITS FOR ACCELERATOR TUBES FROM UHF TO Ka BAND

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Key requirements for microwave power amplifiers for accelerator applications are efficiency, long operating life, and stability in the presence of load mismatch. Pulse widths range from microseconds to CW and frequencies vary from UHF to S-band in conventional accelerator systems. Future machines could require frequencies up to Ka band in order to take advantage of the economically favorable scaling of accelerator size with shorter rf wavelengths[1]. These tube requirements can be met by resonant output circuit devices: klystrons for UHF to X-band, and gyroklystrons up to Ka band.

I. Klystrons

For the high power levels of interest for accelerators, limitations in two key areas, the electron gun and the interaction circuit, define the boundaries of peak and average power levels accessible at various frequencies using a klystron. While design of other parts of the tube such as the output window and collector are obviously important to a successful tube design, they are of secondary interest for purposes of this discussion.

a. Electron Gun Design Limits

Voltage standoff between the accelerating electrodes in the electron gun is a function of the complicated phenomenon of avalanche breakdown but is known to be subject to the limits described by Staprans[2]. For reliable operation at a given pulse width the maximum standoff voltage scales with the 0.8 power of the electrode spacing. This implies that at higher beam voltages, electric field strengths in the gun must be reduced. Voltage standoff also varies strongly with beam pulse width[2]. These dependencies imply that the peak voltage capability of a given gun design improves markedly in the transition from CW to short pulse (~10 μsec) operation. One approach to circumventing the limit on peak beam voltage is to use multiple series electrodes separated by insulating ceramics in order to divide up the total beam potential into a series of smaller potentials[3].

Until recently the emission capability of oxide cathodes limited the peak cathode current densities in multimegawatt electron guns to 5-6 A/cm^2 for short pulse widths. Cathodes known as "M-type", which are made from a new generation of materials, are not subject to emission droop during the current pulse[4]. These cathodes are now being designed into production tubes and are capable of over 10 A/cm^2. The M-type cathodes have effectively removed cathode emitter technology as a primary limitation on the capabilities of electron guns.

Creation of beam optics adequate to avoid beam scalloping (spatial undulation of the beam caused by design errors in gun electrode and iron polepiece shapes) first requires a two-dimensional computer simulation of the beam optics including the effects of space charge. The second step is experimental analysis and subsequent adjustment of the optics in a beam analyzer. The state of the art in klystron design now allows us to design for high quality beams with perveances in the range 0.3 to 2 μa/v$^{3/2}$, with beam area convergence ratios from 4:1 to greater than 100:1. A family of 500 kW CW S-band klystrons has been developed at Varian using this gun design method. At rated power output these tubes have typical body interception currents of 0.06% of the beam current; this represents excellent beam quality and will result in improved tube reliability.

b. Output Circuit Design Limits

In klystrons, efficient operation means that the electrons lose most of their energy in the rf gap in the output cavity. This implies that the rf output gap voltage can be of the order of the beam voltage and rf gap voltage breakdown does indeed represent a design limit in klystrons. As with other avalanche breakdown phenomena, the limits on rf gap voltage can be relaxed as the rf pulse width is shortened. One approach to bypass the gap voltage limit is to split up the total gap voltage by having multiple rf gaps in the output cavity[5]. This approach, known as the extended interaction klystron (EIK), has been proven successful at Varian on a 1 MW pulsed radar klystron at S-band and a 1 MW CW experimental klystron at X-band.

Load mismatch also affects the voltage at the output gap in a manner which depends on the phase and amplitude of the mismatch. Typically, for weak mismatches (VSWR $\leq$ 1.2:1) the klystron power output will change slightly. For moderate mismatches (VSWR $\leq$ 1.5:1) some significant degradation in tube performance will occur. Severe mismatches (VSWR > 2:1) can lead to gap voltage breakdown, window arcing, and if the condition persists, tube damage. Under certain conditions, by controlling the phase of a known mismatch, the accelerator designer can allow load mismatch to occur in such a way that the klystron output becomes overcoupled. This decreases klystron power output without damaging the tube.

Ohmic losses in the output cavity due to rf skin currents in the cavity walls limit the power capability of klystrons above X-band. The volume of conduction material in which the rf energy is dissipated is roughly equal to the rf skin depth times the resonator's inside surface area. Thus the mass of material which is heated by rf losses scales as frequency to the minus five-halves power. To avoid melting this material, the power capability of klystrons must fall off at high frequencies in a similar manner. The EIK concept is also useful for extending this rf dissipation limit. In the EIK output structure, which is comprised of several coupled cavities, the power dissipation in each cavity is equal to the total dissipation divided by the number of cavities.

Klystron efficiency is optimized when all electrons in the output cavity gap have the optimum phase with respect to the rf field. When this group of electrons becomes "debunched" in phase, efficiency suffers. Excessive space charge forces in the beam are one cause of debunching. For this reason, high efficiency CW klystrons are designed with low perveance ($\lesssim$ 1.0 μA/v$^{3/2}$) to minimize the debunching due to space charge forces. For high peak power pulsed klystrons, the perveance is increased (to 2.0 μA/v$^{3/2}$ or greater) to allow operation at practical beam voltages, with some sacrifice in device efficiency.

c. Performance Limits for Klystrons

When the power limits for each of the critical klystron design parameters are plotted as a function of frequency, the klystron technology limit at any given frequency is defined by the lowest design parameter limit at that frequency. Technology limit curves for CW tubes are shown in fig. 1. The CW klystron limit has been well defined by a number of production or laboratory devices. At the low frequency end, output cavity sizes are large because of the long wavelength and the output power is limited by practical CW beam voltages and perveances which allow reasonable efficiency. At the high frequency end, gap voltage breakdown and rf dissipation in the output cavity cause a rapid decline in the power limit.

For pulsed tubes the power limits are improved

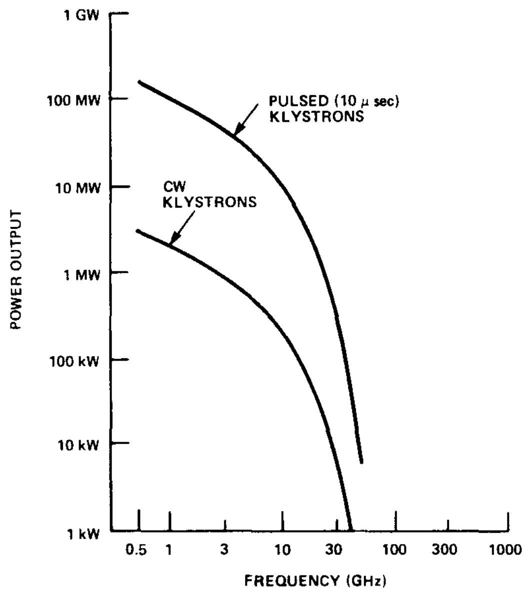

Fig. 1. Technology Limits for Pulsed and CW Klystrons.

because voltage breakdown limits are relaxed at short pulse widths and because rf dissipation limits are set by average rather than peak power levels. Peak power limits are therefore typically a factor of fifty higher than for CW tubes as depicted by the upper curve in fig. 1. A noteworthy point near this curve is the recently demonstrated 50 MW S-band klystron under development at SLAC.

d. Klystron Reliability

Klystron reliability, as measured by mean time between failures (MTBF) in hours of cathode heater operation, is given for several documented cases in table I. Common failure modes for high power tubes are rf circuit damage due to beam interception or rf arcing, output window failure, and vacuum envelope failure at thermally stressed points in the tube. The MTBF for a given design is a function of the demands of the system environment which include such factors as mechanical vibration, mismatch or arcing in the transmission line, effectiveness of protective devices, and level of skill of operating personnel. For a given application, the MTBF of a particular tube may be improved by reducing peak and average power requirements. Table I shows that pulsed accelerator klystrons have MTBF's of 20,000 - 40,000 hours while CW accelerator klystrons have MTBF's in the 15,000-20,000 hour range.

TABLE I
RELIABILITY FOR HIGH POWER KLYSTRONS

Tube Type	System	Peak Power (MW)	Duty	Frequency (GHz)	MTBF (Hours x 1000)
VA-842	Radar	1.25	Pulsed	0.425	55
VA-938	Linac	4.0	Pulsed	2.856	35
VKS-8252	Linac	5.5	Pulsed	2.856	32
VA-963A	Radar	6.5	Pulsed	1.300	76
RCA	SLAC	30	Pulsed	2.856	40
SLAC	SLAC	35	Pulsed	2.856	20
SLAC	SPEAR	0.125	CW	0.358	20
SLAC	PEP	0.500	CW	0.353	15

II. Gyroklystrons

The physical interaction known as the "gyrotron" interaction requires axial magnetic fields for which the electron cyclotron frequency in the electron beam of the tube is equal to the rf frequency[6]. Under the proper conditions, the beam electrons, which follow helical trajectories through the tube, become bunched in their phase of cyclotron rotation and give up energy to transverse electric (TE) microwave fields.

"Gyroklystron" denotes a device configuration which contains a series of resonant cavities connected by beam drift tunnels. Drive power is applied to the first cavity and amplified power is extracted from the last cavity, just as in a klystron. The difference is that the cavities can be operated in higher order TE modes rather than the TM_{010} modes used in klystrons. Hence, the allowed size of the beam and interaction structure can be significantly larger, and the power capabilities at a given frequency concomitantly higher.

a. Electron Gun Design Limits

A gyroklystron beam contains electrons orbiting along helical paths and it is only the rotational kinetic energy of the electrons which can interact with the rf fields. Thus, in addition to the beam voltage and beam current, the ratio of rotational to translational energy on the beam, denoted $\alpha^2 \equiv V_\perp^2/V_\parallel^2$, effects the efficiency of the device. The figure of merit for "beam quality" in a gyroklystron is not "beam scalloping" but relative spread in parallel electron velocities in the interaction region, denoted $\Delta V_\parallel/V_\parallel$. Parallel velocity spread causes debunching of phase-bunched electrons in the microwave interaction region and thereby degrades device efficiency. As a consequence of the magnetic compression of the beam from the gun to the cyclotron resonance region, small velocity spreads in the gun are magnified by the factor α^2 by the time the particles reach the microwave circuit. Hence, gun designs attempt to minimize $\Delta V_\parallel/V_\parallel$ (~5% is acceptable for gyroklystrons), while values of α = 1.5 are considered to give the best compromise between beam quality and extractable energy on the beam.

Qualitatively, the technology limits for high voltage standoff in the electron gun are the same as for klystrons. However, since the beam sizes allowed by the overmoded gyroklystron resonators are larger than those for klystrons, achievable beam perveances are higher as well.

b. Output Cavity Design Limits

The choice of resonant mode for the output cavity is a function of rf dissipation in the cavity. As in klystrons the power density caused by rf dissipation scales proportional to frequency to the five-halves power, for a given cavity mode. However, by a choice of higher order mode the cavity can be increased in diameter while remaining resonant at the same frequency. The rf dissipation per unit area is thereby decreased and the power capability of the device is improved substantially. Two constraints limit the tube designer from using an arbitrarily high order of cavity mode.

In typical gyrotron designs the TE^o_{mn1} cavity mode is coupled to an analogous output waveguide mode TE^o_{mn}. If mode purity is an important property for the signal delivered to the customer's load, retaining the required mode purity beyond the exit of the output cavity and in the overmoded transmission line is increasingly difficult with higher mode number. Mode conversion ($TE^o_{mn} \leftrightarrow TE^o_{m'n'}$) and polarization conversion (linear $\leftrightarrow$ circular) also become more difficult.

A second constraint on choice of cavity mode is due to the phenomenon of mode competition in the gyroklystron cavities. Modes with similar resonant frequencies and standing wave field profiles can compete with the desired mode for beam power.

As a generalization, for a given resonator frequency, the larger the cavity diameter required to support the operating mode, the more modes will be capable of mode competition. The choice of cavity mode for any new tube design involves a study of the tradeoffs between output mode purity and convertibility, susceptibility to mode competition, and rf dissipation in the cavity walls.

c. CW Output Window Design Limits

In order to reduce the rf power density at the output window to levels which do not cause rf breakdown on the air side of the window, the window is chosen to be many wavelengths (overmoded) in diameter for the power levels generated by the gyroklystron. (For the same reason the waveguide used in the external transmission line system must also be overmoded.) In addition, rf power dissipation in the ceramic window can lead to excessive thermal stresses. This problem is solved by forcing a fluorocarbon coolant between the faces of a pair of planar window discs separated by a narrow gap. Power levels of 340 kW CW at 28 GHz and 200 kW CW at 60 GHz have been demonstrated with this type of window design in gyrotron oscillators[7].

d. Performance Limits for Gyroklystrons

High peak and average power gyroklystron amplifiers do not yet exist as production microwave tubes. The major unknown in their successful development is the design of a stable rf interaction circuit with adequate gain and efficiency. However, technology for electron guns, collectors, and windows already developed for gyrotron oscillators is directly applicable to gyroklystron design. Thus, based on design limits and scaling laws described above, we have drawn curves for presumed performance limits for gyroklystrons in fig. 2. The position of the curves with respect to the ordinate were chosen by drawing the curves through demonstrated performance data for pulsed and CW gyrotron oscillators.

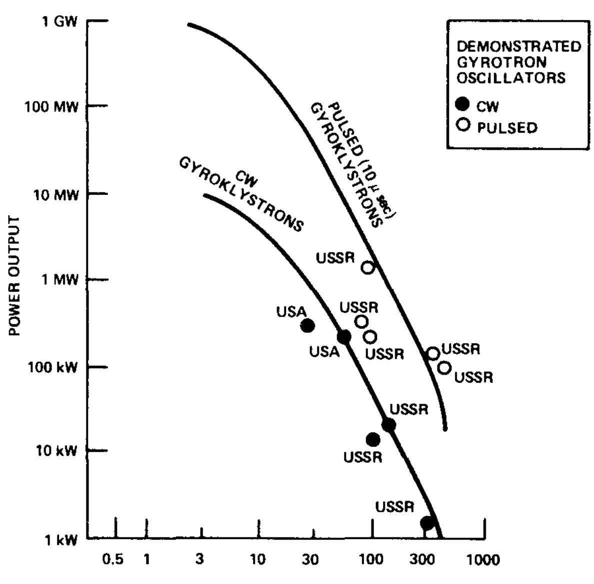

Fig. 2. Technology Limits for Pulsed and CW Gyroklystrons.

In the range of frequencies where CW gyrotron oscillators have been demonstrated, the minus-five-halves scaling of power with frequency is characteristic of the rf dissipation limit for the output cavity modes (e.g., TE^{o}_{021}) which were used in these devices. However, the CW power limit for output windows in this frequency range probably lies only a factor of 2 or 3 above the curve. Below 28 GHz, no demonstrated data exists, but the power curves must plateau at low frequencies as they do for klystrons, due to practical limits in achievable CW beam voltage at reasonable beam perveance.

Soviet results for pulsed (~10 μsec) gyrotron oscillators are shown with the presumed technology limit for pulsed gyroklystron amplifiers represented by the upper curve in fig. 2. Here again as was true for klystrons, short pulse operations allow an increase in peak power over the CW limit by about a factor of fifty.

e. Gyroklystron Reliability

Gyroklystrons are qualitatively similar to klystrons in the mechanical assembly techniques and materials employed in their construction, and in their modes of failure as well. For example, vacuum envelope failures which have occurred in 200 kW CW gyrotrons have been caused most frequently by output window failure or by failure of metal-to-metal joints in other thermally stressed areas of the tube. It is reasonable to expect that once gyroklystron designs have been thoroughly evaluated and refined, MTBF's similar to those given in table I can be expected for pulsed and CW devices. Meanwhile, lower MTBF's (~5,000-10,000 hours) will be encountered while the technology matures and the gyroklystron designers and accelerator designers become familiar with each others' new interfacing problems. Fortunately, some promising reliability data is already available for gyrotron technology. A 200 kW CW 28 GHz gyrotron has thus far accumulated a total of over 2000 hours of operation at both Varian and TRW/Redondo Beach without failure.

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