SLAC-PUB-3324
April 1984
(A)

HIGH POWER RF KLYSTRONS FOR LINEAR ACCELERATORS*

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Summary

Recent klystron developments at SLAC are described. The standard 40 MW klystron, which typically operates at 35 MW on the SLAC linac, is the starting point for the push to higher peak and average power. The standard tube is capable of a 2.5 μs RF pulse width at 360 pps. For the SLC a 50 MW klystron capable of 5 μs pulse width at 180 pps is under development. Another tube currently being worked on is a 150 MW klystron capable of 1 μs RF and 180 pps.

Design criteria and actual operating experience for both developmental tubes are described. A one-dimensional large signal code was used to design the tubes. Calculated operating parameters obtained from this code are presented. Based on standard klystron experience at SLAC high voltage breakdown, instabilities and RF window breakdown were expected to be problem areas. Current experience in those problem areas on the new tube designs is summarized. In the case of the SLC klystron 50 MW at rated average power has been obtained at 315 kV with an efficiency of 45%. The fault rate has been found to be as low as one fault per 8 hour shift. The first 150 MW klystron had a conventional output cavity and produced 105 MW at the design beam voltage of 450 kV. At 475 kV a power of 122 MW with an efficiency of 43% were obtained. Design changes to obtain higher power and efficiency are incorporated in the second 150 MW tube and projections are made for future tubes.

Introduction

Since the beginning of SLAC there has been an on-going program to improve the klystrons powering the accelerator. In fact the permanent magnet focused 20 MW klystrons first used at SLAC were based on developments started at Stanford University right after World War II.[1] A summary of the development and early performance of the 20 MW klystrons was given by Lebacqz.[2] Subsequently the operating voltage of the klystrons was raised to 265 kV yielding a nominal power output per klystron of 30 MW. More recently the interaction space of the klystron was redesigned so that 40 MW of peak power could be obtained at 270 kV with an interaction efficiency of 50%. This tube was designated the XK-5 and there are approximately 140 of these currently in use. Lebacqz summarized the life history of all high power SLAC klystrons at the 1979 Linear Accelerator Conference.[3] The cumulative MTBF of all klystrons at SLAC is slightly higher now. It stands at nearly 25,000 hours. In this paper recent work at SLAC on high power klystrons will first be reviewed and then some suggestions for future activities will be made.

SLAC High Power Klystrons

The klystron having been built at SLAC until now is the XK-5. On the linac, where the operating voltage is 265 kV, the tube puts out between 34 and 37 MW. It is capable of 2.5 μs RF at 360 pps, even though in recent years the linac PRF has not exceeded 180 pps. The tube has an oxide coated cathode and is permanent magnet focused. Table I lists other operating parameters for the XK-5. Also included in Table I are the operating parameters for two other klystrons recently developed at SLAC.

Table I
SLAC High Power Klystron Parameters

	XK-5	5045	150 MW
Operating Voltage (kV)	265	315	450
Perveance (μP)	2.1	2.0	2.0
Peak Beam Current (A)	286	354	600
Frequency (MHz)	2856	2856	2856
Power Output (MW)	36	50	150
Repetition Frequency (Hz)	360	180	180
Efficiency	0.47	0.45	0.55
Gain (dB)	50	50	50
RF Pulse Width (μs)	2.5	5.0	1.0
Beam Pulse Width (μs)	3.35	6.0	2.0
Cathode Type	Oxide	Dispenser	Oxide
Focusing Magnet	Permanent	Electro.	Electro.

The second one listed is the one earmarked for the SLC (SLAC linear collider). The requirement is for a 50 MW peak, 45 kW average power tube. Hence it is designated as the 5045. Note that for this tube the operating voltage is 315 kV. Focusing is by electromagnet and a dispenser cathode has been chosen. Both scandate and M-type cathodes have been used. Almost no long-term experience exists in the industry with cathodes operating at a peak current density of 6.8 A/cm^2 required in the 5045 klystron, but to date the results are encouraging. The scandate cathode in particular operates at a low enough temperature so that one can project a cathode life of more than 20,000 hours. Note that the 5045 klystron, when used in the SLC, will operated with the SLED (SLAC energy doubler) system. Thus an RF pulse width of 5 μs is required at 180 pps. Several full specification tubes have been tested to date, with fewer than two high voltage breakdowns in an eight hour shift. Sufficient data is not yet available, but the number of missing or partially missing RF pulses has been observed to be less than one in 50,000 on a number of the experimental tubes. This rate is also acceptable for SLC operation. More details of the 50 MW klystron development have been reported by Lee et al.[4] Figure 1 shows the XK-5 and the 5045 side by side for comparison.

Another klystron has been developed at SLAC in a joint U.S.-Japanese effort. This is a 150 MW klystron and its parameters are also shown in Table I. This tube is designed for 450 kV and 1 μs RF pulse length. The results on the first tube will be described in more detail below. Figure 2 shows a photograph. Note that the interaction length of this tube is significantly longer than that for the two other tubes because of the higher operating voltage.

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* Work supported by the Department of Energy, contract DE-AC03-76SF00515

Invited paper presented at the 1984 Linear Accelerator Conference,
Seeheim/Darmstadt, West Germany, May 7-11, 1984.

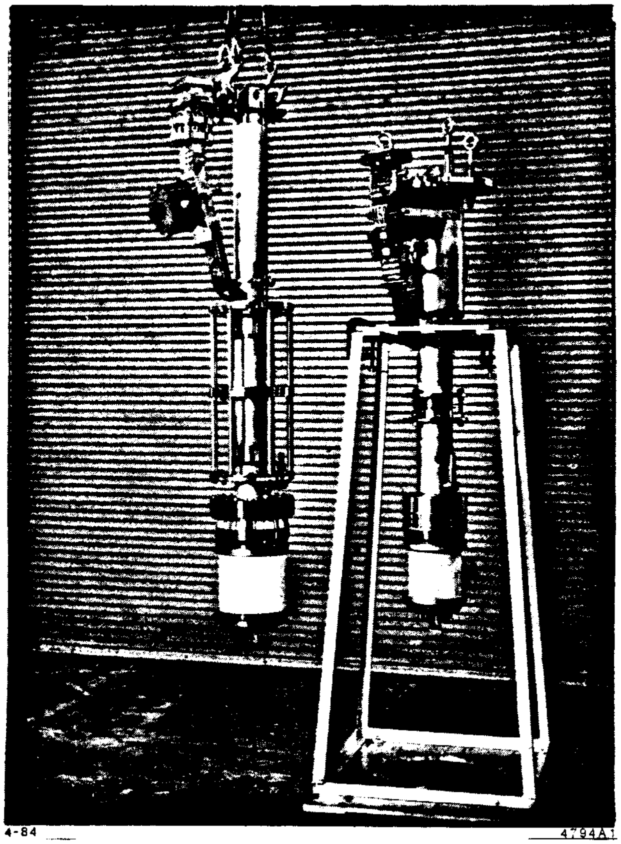

Fig. 1. SLAC 50 and 40 MW klystrons.

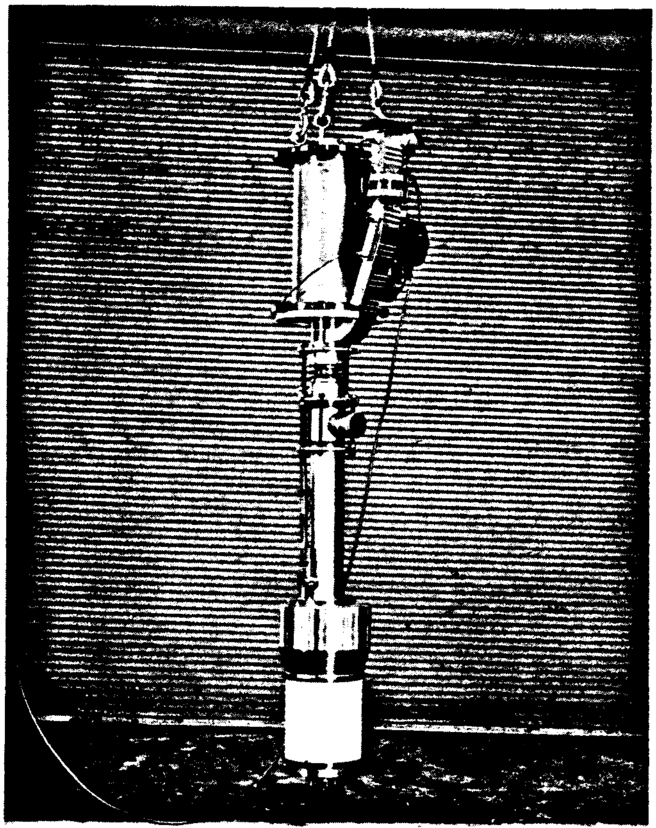

Fig. 2. 150 MW klystron.

Computations

There are two large-signal klystron design codes operational at SLAC. One is a one-dimensional code based on polarization variables. Some work has been done on a two-dimensional code of the same nature, but is not yet available for use. The other operational code is a one-dimensional disk model code based on a Lagrangian type of analysis. A full time-stepping formulation is used to integrate the equations of motion from the entrance to the exit of the drift tube. A gridless gap is assumed and a Gaussian function simulates the field distribution. Relativistic and space charge effects are included. Double output gaps as well as higher harmonic cavities can be simulated. A comparison between computations based on this program and actual tube operation is shown in Fig. 3. The agreement for the XK-5 tube is quite good. In the case of the 5045, subsequent tubes showed a little better agreement. Furthermore, the interaction space was redesigned to decrease gain and improve stability. In that case agreement was within five percentage points, which is quite good for a one-dimensional analysis. In Fig. 4 the process of bunching, RF current buildup and the energy exchange along the tube may be clearly seen. Table II lists the interaction space parameters for all three tubes under discussion. The first of the 150 MW klystrons had only a simple output gap. In the second tube a double output gap will be used and so two gap transit angles and the space between the gaps are shown in the table.

Table II
High Power Klystron Interaction Space Parameters

XK – 5 Klystron

Cavity No.	Cavity Freq. (MHz)	Q	Gap Transit Angle (Rad.)	Drift Length (cm)
1	2862	250	0.538	6.566
2	2865	4000	0.418	5.718
3	2870	4000	0.570	17.74
4	2920	4000	0.791	10.505
5	2851	19	0.968	

50 MW Klystron

Cavity No.	Cavity Freq. (MHz)	Q	Gap Transit Angle (Rad.)	Drift Length (cm)
1	2860	200	0.543	5.54
2	2870	2000	0.574	5.54
3	2890	2000	0.662	5.54
4	2910	2000	0.900	28.45
5	2970	2000	0.955	10.41
6	2853	21	1.267	

150 MW Klystron

Cavity No.	Cavity Freq. (MHz)	Q	Gap Transit Angle (Rad.)	Drift Length (cm)
1	2860	150	1.177	13.50
2	2865	2000	0.780	13.50
3	2870	2000	1.197	36.75
4	2940	2000	1.560	11.60,6.86
5	2856	- -	1.560,1.560	

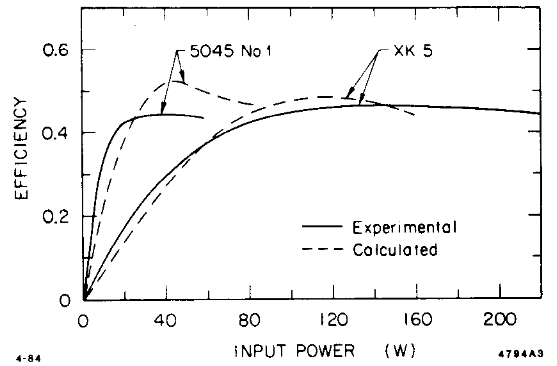

Fig. 3. Comparison of computed and experimental klystron performance.

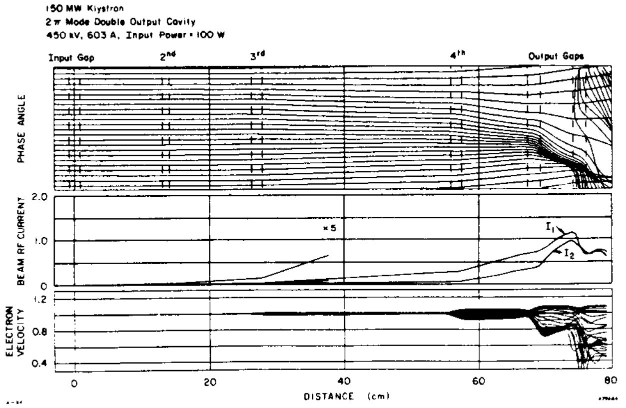

Fig. 4. Graphic display from one-dimensional disk model computer program.

Klystron Performance

In Fig. 5 transfer characteristics for the XK-5 klystron are shown. While the curves shown are for a specific tube, they are representative for the SLAC tubes. The peak power output as a function of operating voltage is plotted in Fig. 6 for two 5045 klystrons. Note that at 320 kV 51 MW was observed on both tubes. The drive power requirement was in the 400 to 600 W range. The gain as well as the power output are affected significantly by the magnetic focusing field. For Fig. 6 the magnetic field was held fixed at a value optimized for 320 kV.

The first 150 MW klystron had two shortcomings. First the microperveance was only 1.84 rather than the design value of 2.0. Second, it was decided to build the first tube with a single output gap. To do so, it was necessary to choose a long gap (1.56 radians according to Table II), in order to minimize the risk of RF breakdown at voltages around 600 kV. Thus coupling was low and the computed efficiency was only 43 percent, as shown in Fig. 7. The tube was operated to 475 kV, a limit set by the test stand. At that level 122 MW was observed. The RF output was clean and the tube was stable. The second and third harmonics were down by 31.7 dB and 34.5 dB, respectively, as measured by the method devised by Fowkes and Wu.[5]

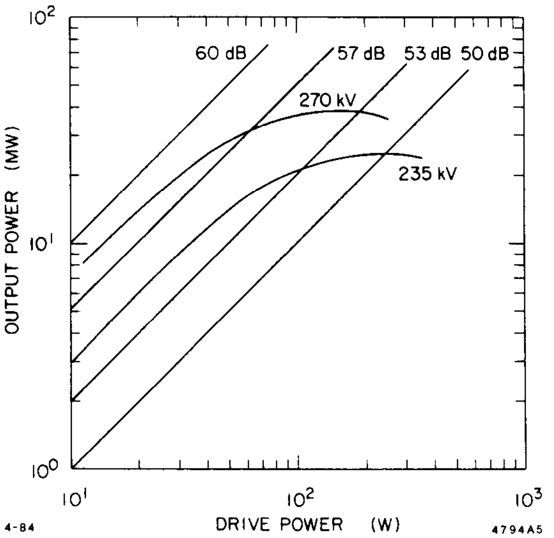

Fig. 5. XK-5 klystron performance.

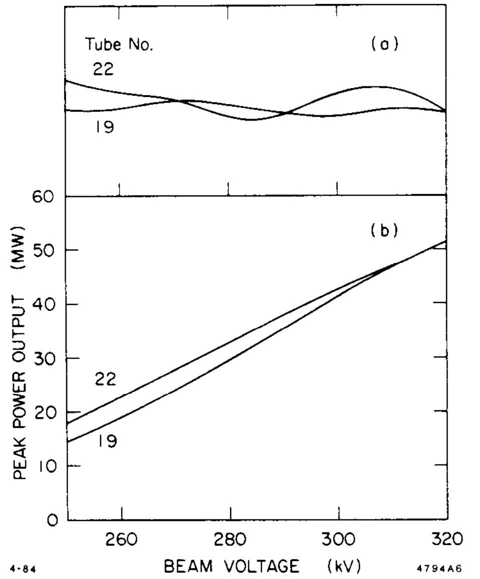

Fig. 6. Performance of two 50 MW klystrons. PRF = 180 pps; pulse length = 5 μs; constant focusing field.

The second 150 MW klystron will have a double gap output cavity and the microperveance will be raised to the intended value of 2.0. The 2π mode was selected for the double output gap. The dimensions are shown in Fig. 8. Ideally one would like to have an impedance of approximately 600 ohms for both gaps for maximum efficiency and equal field distribution. Also, the phase angle ϕ_{11} should be zero in the impedance matrix. ϕ_{22} (and hence ϕ_{12} and ϕ_{21}) can always be made zero by making the last cavity of the two inductively coupled cavities resonant at the signal frequency. By following the method described by Zhao,[6] the design in Fig. 8 was worked out for which the impedance matrix is

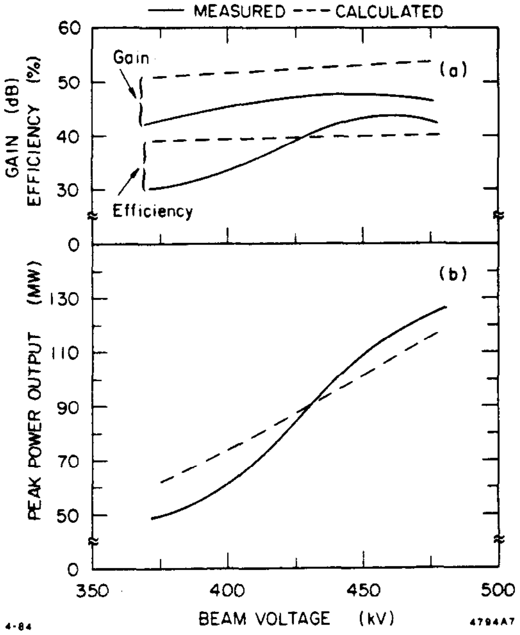

Fig. 7. Performance of 150 MW klystron No. 1. $f_0 =$ 2856 MHz and microperveance = 1.84.

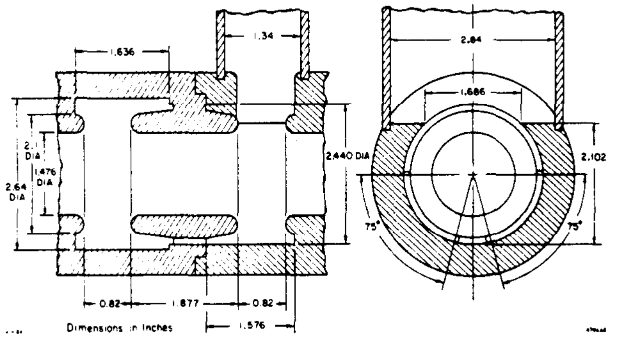

Fig. 8. 2π-mode double-gap output cavity for 150 MW klystron No. 2.

$$Z = \begin{bmatrix} 474 \ \underline{/27^\circ} & 580 \ \underline{/0^\circ} \\ 580 \ \underline{/0^\circ} & 800 \ \underline{/0^\circ} \end{bmatrix} .$$

At 450 kV an efficiency of 50 percent can be computed and the power output is 137 MW, as shown in Fig. 9. Under these conditions 150 MW should be achievable at just under 470 kV.

Electron Guns for High Power Klystrons

Table III shows the relevant gun parameters for the three SLAC klystrons. Note that the cathode loading for the two new klystrons is only slightly greater than for the XK-5. To be conservative the peak gradients are actually lower. Because of the 6.0 μs pulse length of the 5045, that design is the most marginal one from the standpoint of gun breakdown. After careful selection of electrode materials, extensive polishing and careful conditioning, satisfactory fault rates for SLC operation have been obtained, as mentioned above.

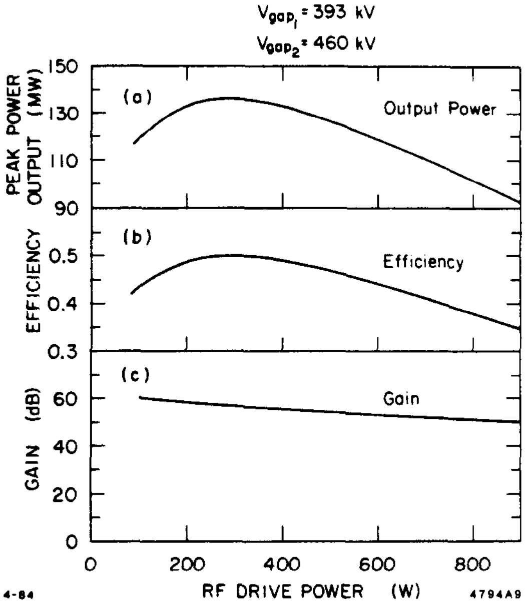

Fig. 9. Calculated performance of 150 MW klystron No. 2. V_0 = 450 kV; I_0 = 600 A; f_0 = 2856 MHz; 2π-mode double gap output.

Table III
SLAC Klystron Gun Parameters

	XK-5	5045	150 MW
Operating Voltage (kV)	270	315	450
Peak Beam Current (A)	295	354	600
Cathode Current Density (A/cm^2)	5.7	6.8	7.0
Cathode Diameter (cm)	7.92	7.96	10.38
Cathode Loading Uniformity	1.51:1	1.7:1	1.44:1
Peak Gradient (kV/cm)	290	225	220
Beam Diameter (cm)	2.00	2.00	2.63
High Voltage Pulse Length (μs)	3.35	6.0	2.0

Window Development

The RF window is usually one of the major problem areas in a high power microwave tube. Historically SLAC klystron windows have had to operate with vaccum on both sides. A window improvement program has been going on for many years. Recently the resonant ring shown in Fig. 10 has been made operational again. It permits window tests quite reliably up to 200 MW and 300 MW has been achieved for relatively short periods. The limit is due to breakdown in the phase shifter used for tuning the ring.

Figure 11 shows the standard SLAC pillbox window used on all klystrons discussed in this paper. The ceramic is Al_2O_3 copper brazed into a CuNi sleeve. Recent tests with Cu sleeves indicate that cooler window operation may be possible. There has been a major effort to optimize the coating applied to the window surfaces for multipactor suppression. TiN currently appears to be the best choice. A major area of concern is erosion of the braze joint. This phenomenon has been observed more frequently as the pulse length was increased from 2.5 to 5.0 μs.

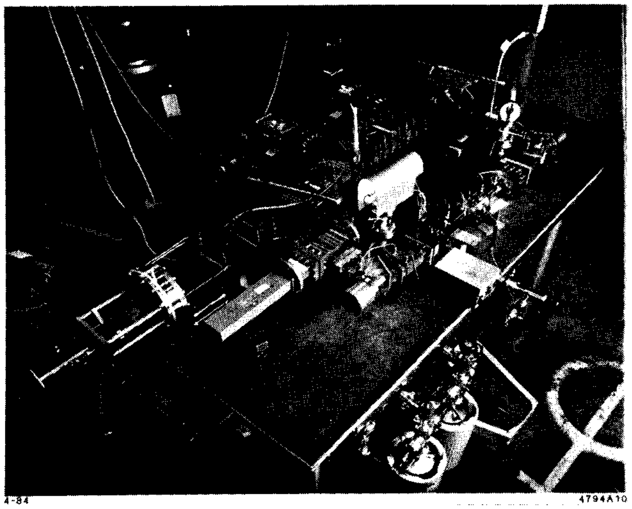

Fig. 10. Resonant ring window test facility.

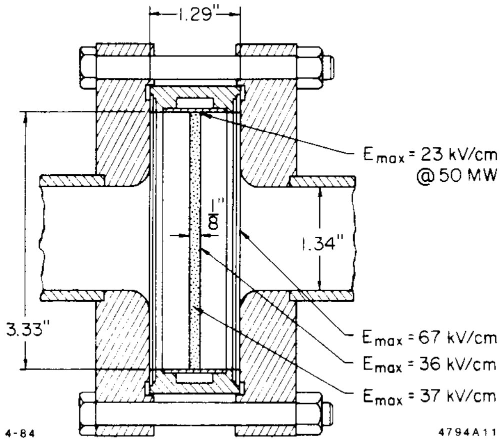

Fig. 11. SLAC S-band pillbox window.

In connection with the 150 MW klystron program a 12.5 cm diameter pillbox window has been designed and tested in the resonant ring. A peak power level of 250 MW at 6 μs could be maintained. Further tests will be made with this window.

Future Work

There are no fundamental limitations which prevent klystrons from being scaled to produce peak powers of several hundred megawatts and possibly a gigawatt. Some years ago, in fact, a klystron with a 15 ns pulse length operating at 3.35 GHz was built with a design peak power of 1 GW, a beam voltage of 1 MW, a beam current of 2 kA and an efficiency of 50 percent.[7] The tube could not be tested to full power because of modulator limitations. If a need for such high power RF sources exists, R & D work on several key components needs to be undertaken. Windows, gun breakdown and RF breakdown are the most obvious areas. Cathode emission limitations are another area of concern. In a klystron, which is the most likely candidate in the near term for such power levels, a magnetron injection gun could be used. This type of gun gives a hollow beam and so a good efficiency with a higher perveance could be obtained. In this way extremely high voltages could be avoided. Historically beams from magnetron injection guns have been unstable, but there has been much work lately with these guns for gyrotrons. Such guns are much better understood now.

When relativistic effects are included in klystron calculations, one is able to predict a higher efficiency and lower gain. In practice the effect has not been very great, probably because of space charge effects. If a highly relativistic, well-bunched beam could be injected into a klystron output cavity, a very good efficiency should be possible. Herrmannsfeldt at SLAC has made calculations for a 105 A, 500 kV beam.[8] Using the 3-D particle-in-cell code MASK an efficiency above 70 percent seems possible. Such a tightly bunched beam could be obtained from a field emission cathode, a laser cathode or possibly a semiconductor cathode. The first has been pursued for more conventional voltage levels by Spindt at SRI.[9] Emission tests have been reported at 300 A/cm^2 from small arrays of tips (15-30 tips spaced in 9 μm centers). Packing densities of 5.8×10^6 tips/cm^2 have been achieved. A 100 tip array has demonstrated over 8 years of operation at cathode loadings in the 50 μA/tip range. Unfortunately, discharges may occur after many hours of stable operation producing a chain reaction failure if one tip arcs over. The laser cathode also has exciting possibilities for this application. A laser could probably be more easily modulated at an S-Band frequency than the voltage near a field emitting tip. According to Sinclair of SLAC current densities well in excess of 100 A/cm^2 should be possible,[10] but unfortunately not much life experience has been reported to date.

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