ANALYTIC INVESTIGATION OF EFFICIENCY AND PERFORMANCE LIMITS IN KLYSTRON AMPLIFIERS USING MULTIDIMENSIONAL COMPUTER PROGRAMS; MULTI-STAGE DEPRESSED COLLECTORS; AND THERMIONIC CATHODE LIFE STUDIES.

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Introduction

In 1972 this author together with L.U. Albers performed an extensive parametric investigation of the extraction of energy in output gaps of klystron amplifiers, using our own 3-D computer programs. Due to complexity of the program which used a hydrodynamic, axially and radially deformable disk-ring model and the resulting long computing time we limited our investigation, Ref. 1, to the output gap, by far the most important and difficult part of the klystron interaction. As inputs best results from independent studies at G.E. by T. Mihran, Ref. 2 and at Varian, Ref. 3, by E. Lien were used to initiate the starting conditions for the electrons and the RF voltage using our program. Although this method of computation is less exact than processing the entire klystron interaction in 3-Dimensions we verified that, for a confined flow focused beam throughout the penultimate cavity, radial velocities remain very small and the beam is highly laminar. It was, therefore, concluded that possible errors resulting from treating only the output cavity in 3-D would remain small.

Discussion of Results

We proceed now with the discussion of the computer results. Figure 1 shows the cross-section of the ring model used in computations and the degree of complexity and care applied to compute accurately the radial and axial deformation of the rings and the space charge forces. The price paid for this effort - the computing time - was felt to be justified for the one time verification. Figure 2 shows typical axial and radial space charge functions. In agreement with basic theory the radial functions obey Gauss' law inside the beam and the axial space charge force is zero at the tunnel wall r=a.

Efficiency

Let us now turn to the discussion of computed efficiencies. Figure 3 shows a plot of efficiency versus $\beta_e \cdot a$ for two bunching levels, $i_1 = 1.81\, I_0$ and $i_1 = 1.64\, I_0$, $B = 2.5 \times B_{BR}$, and $0.5\,\mu$ perveance. The voltage swings α are 1.10, 1.05, and 1.0, respectively. The $1.81\, I_0$ bunching is characterized by a very compact bunch with a small velocity spread and absence of a typical antibunch disk since the maximum-velocity past the output gap is only $1.14\, u_0$. As can be seen from the plots, the efficiency seems to decrease linearly with increasing $\beta_e a$ with a slope of approximately 2.5 percent points efficiency loss for each 0.1 radian increase in $\beta_e a$. Note that b/a, β_e, and $2.\ell$ were held constant and only a was permitted to increase. Thus at large $\beta_e a$ values the aspect ratio ℓ/a is small; the RF fields penetrate deeper into the tunnels than in cases of narrow tunnels. We observed that many disks were caught in the long fringes and experienced a post-acceleration when the RF field reverses its phase. This phase reversal is also responsible for the increase in current interception that is marked in percentage points, since the radial RF fields action changes from converging into diverging. Computations at $\beta_e a > 1$ were not continued due to a rapid increase in interception to impractical levels.

The above finding of increasing η with decreasing $\beta_e a$ is confirmed by a number of new experimental results in high-efficiency klystrons and TWT designs, mainly at Varian (3), but it seems to disagree with the estimates of Mihran (4), and the very early finding by Cutler (5). It should be remembered that Mihran's conclusions were based on the behavior of rigid disks and did not treat the energy extraction, while Cutler's experiments with helical structures cannot be considered representative of a solid wall tunnel and a discrete gap with regard to RF and space-charge fields. The author knows that the constant bunching level assumed for computing the straight lines of Figure 3 cannot be strictly realized in practical designs. The value $\beta_e a = 0.5$ is probably as small as can be realized at high frequencies and further decrease in $\beta_e a$ would only increase the demands upon the focusing fields to excessive levels.

A physical explanation for the behavior presented in Figure 3 was recently found by researchers at Varian, notably E. Lien, who showed that a favorable conversion of second harmonic bunching into fundamental bunching takes place at small values $\beta_e a$.

Another important selection criteria for high efficiency designs is the choice of perveance which, in turn, is a measure of space charge forces in the beam. Large space charge increases the degree of the velocity spread in beams of all tube types and also decreases the efficiency of depressed collectors. If we again assume constant bunching, then Figure 4 demonstrates clearly the destructive effects of increasing perveance on the electronic efficiency of the output gap. Note also the increase of interceptions. On the other hand, to achieve high overall efficiency, the circuit efficiency, η_{ck} must be as high as possible which requires larger values of perveances. Thus, a compromise is required. This author suggested a value around 0.25 μperv. as most reasonable selection.

Still another selection must be made concerning the length of the output gap. The results are plotted in Figure 5 with θ_o, the output gap length in radius, as parameter and the output voltage α out as abscissa. Fortunately, within a range of $\theta_o = 20^o$ to 40^o, η remains insensitive to gap length.

Parametric Optimization of the Output Gap Performance

If one assumes, as we did throughout this paper, that the quality and magnitude of the bunching used in this study was very close to a practical optimum, then it should be possible to perform a parametric computer optimization of the electronic klystron efficiency. Note that the value of $i_1/I_o = 1.81$ obtained by E. Lien is close to the theoretical limit $i_1/I_o = 2$ and that this design resulted in a very compact bunch and absence of a typical antibunch disk since the maximum velocity past the output gap was only $1.14 u_0$. With this justification we proceed to discuss Figure 6 which is the most important result of this study.

Figure 6 is a summary of some of our computations executed for disk distribution and klystron design parameters as supplied by Mihran from General Electric and Lien from Varian. Our results are plotted with solid and dotted lines as η versus phase. Available for comparison were results published by Mihran et al. (2) and by Varian (3), both with one-dimensional programs. The top circle indicates an 83 percent value as computed by Lien (3), (and private communication) who measured 75 percent with 2 percent RF interception and the triangle, an 82 percent value as computed by Mihran et al. (2) Note that both investigators used almost identical bunching levels with, however, different $\beta_e a$ values of 0.485 and 0.75, respectively. Disregarding at first interception (which cannot be computed with one-dimensional models) it is seen from Figure 6 that Lien's number is about 3 percent and Mihran's about 10 percent points higher than our result (which indicates 6 percent current interception at η = 0.806). The strong dependence of η on $\beta_e a$ is evident. A more sensible evaluation is possible if not only measured and computed efficiencies but also interceptions are compared. Turning now to Table I which summarizes measured (by Lien) and computed (author's program) results, excellent agreement in efficiencies is evident. At α = 1.08 the agreement in interception is also very good and becomes less good with decreasing α where measurements indicate some residual interception while our program indicates none.

It is believed that this difference is more due to the "nonideal" features of tubes than to program errors. Also, the level of interception in Lien's klystron was very small to begin with.

A comparison between Mihran's measurements of η = 0.62 with our computations was not possible because Mihran's measurements were carried out at a perveance of 0.72×10^{-6} instead of 0.5×10^{-6} and disk distribution for the higher perveance was not available.

In computing the above cases the correct field distribution between the tunnel tips, as discussed in Ref. 6, was used. The detail is illustrated in Figure 7, case (C) where the ratio of the E_z field at the tunnel tips to that in a middle of the gap at r=a was approximately 2.5. Using the correct, actual field and not the uniform one is important for the trajections of slow electrons moving close to r=a.

Conclusions

A very accurate mathematical model and computer program for the computation of electronic interaction, electron trajectories, interceptions, and efficiency was developed for the output cavity of a klystron amplifier. It is concluded that one-dimensional programs yield efficiencies that are approximately 10 percent points too high at η levels > 0.7. It has been confirmed that $\eta_e \approx 0.75$, with a few percent interception, is possible and that $\eta_e \approx 0.8$ could be obtained with 6 percent "ideal" interception. With the augmentation by a novel depressed collector, overall efficiencies of 80-85 percent seem possible. A very important conclusion is the result that η increases linearly with decreasing $\beta_e a$, at least in the range $0.4 < \beta_e a < 1.0$. Another important conclusion is that efficiency increases initially with interceptions. At $\eta \geqslant 0.7$ transverse velocities of many rings are comparable to axial components and exit angles up to 30^o were observed.

Multi-Stage Depressed Collectors

The combination of LeRC developed Multi-Stage Depressed Collectors (MDC) and Spent Beam Refocusing Schemes has led to demonstration of highest collector and overall efficiency when applied to TWT's with moderate electronic efficiencies ($\eta_e < 25\%$), Ref. 7. MDC efficiencies in excess of 97% were measured on dc beams of medium perveance (0.5 μ perv) and more than 85% MDC efficiency on spent beams with 20% electronic efficiency. This author developed simple relations for predicting the MDC and the overall efficiency, η_{ov}, for TWT's in Ref. (8):

$$\eta_{col} = \eta_{DC}\left[1 - \frac{1}{N-1} \frac{f(\mu perv)\sqrt[3]{\eta_e \cdot \mu perv}}{2 - f(\mu perv)\cdot\sqrt[3]{\eta_e \cdot \mu perv}}\right]. \quad (1)$$

$$\eta_{ov} = \frac{\eta_{ck} \cdot \eta_e}{1 - \eta_{col} + \eta_{col}\left(\eta_e + \frac{P_{INT}}{P_o}\right) + \frac{P_{SOL}}{P_o}} \quad (2)$$

(Pint, Psol designate, respectively, the intercepted and solenoid power).

These relations may be derived, Ref. (8), from a more basic relation derived by this author, also in Ref. (8), for the smallest (normalized) energy of an electron in the spent beam of a helical TWT:

$$\frac{V_{min}}{V_o} = 1 - f(\mu perv)\cdot\sqrt[3]{\eta_e \cdot \mu perv} \quad (3)$$

The factor f(μ perv) is a simple function of the perveance ranging from f(o)= 1.26 to f(2) = 0.8 for helical TWT's. It assumes different (from those quoted above) but as yet unknown values for coupled cavity TWT's and klystrons. Relation (3) holds also below saturation and does not contain any small signal quantities. Were f(μ perv) known for klystrons it could be then applied to eqs. (1) and (2).

During the earlier days of our collector work at LeRC we did some collector work in conjunction with klystrons of microperv .75 at C-Band and 0.5 at Ku band and $\eta_e \approx 40\%$. Highest then achieved collector efficiencies were approximately 65% resulting in overall efficiencies of about only 50% due to interception and poor circuit efficiencies (less than 90%). A klystron with 80% electronic efficiency has a very unfavorable velocity spread that will make the design of a MDC even more difficult because of the presence of majority of rings at the output whose velocities are $< 0.2 u_o$. This author doubts that a MDC efficiency of more than 50% could be practically realized. This fact plus the presence of interception, circuit losses ($\eta_{ck} \approx 0.95$), the solenoid power and a complex power supply are likely to limit the effective RF output efficiency to below 85%.

Cathodes

Cathode performance and cathode life are the main limiting factors to the reliability and long life of microwave amplifiers. The Microwave Amplifier Group at LeRC was and is, for this reason, engaged and committed to testing and analyzing high performance impregnated tungsten matrix cathodes since 1971. Figure A shows the results of long life tests, carried out in real tubes at a density of $2A/cm^2$ on a large number of samples. At $2A/cm^2$ the standard Philips B-cathode has a useful life of about 40,000 hours. The M cathode, the most promising and interesting of the matrix type cathodes, is expected to perform for 8-10 years at $2A/cm^2$ judging from the recorded performance to date. Since the SPS klystron would require a cathode loading density of only 1 or less A/cm^2, commensurate with a true cathode temperature of about 980°C, an educated guess would lead us to an estimated life of perhaps 20 years. Actual test results of this duration are, of course, not available at all and great caution must be exercised in making predictions for system life exceeding 15 years.

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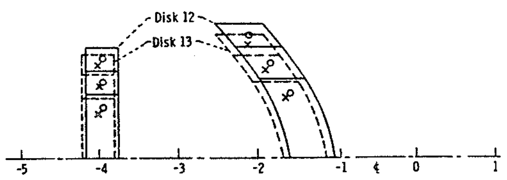

(b)

Fig. 1. (a) Effect of source ring on reference ring. (b) Typical overlapping and deformation of disks 12 and 13. Crosses and circles indicate centers of rings. Position −4 is prior and position −2 past the output gap.

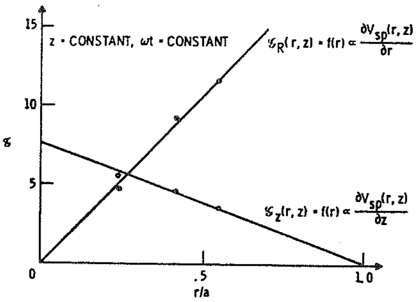

Fig. 2. Typical axial and radial space-charge functions of the beam in the output gap.

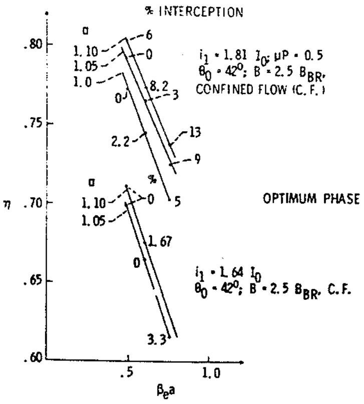

Fig. 3. Efficiency versus $\beta_e a$ with voltage swing α_0 as parameter. Current interception is listed in percent points.

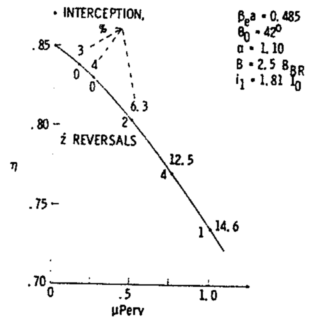

Fig. 4. Efficiency versus perveance assuming constant bunching level. Interceptions and velocity reversals are listed at computed points.

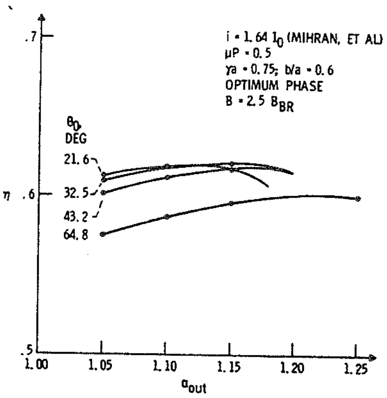

Fig. 5. Efficiency versus output voltage $\alpha = \hat{v}/v_0$ with output gap angle θ_0 as parameter; phase adjusted for highest efficiency.

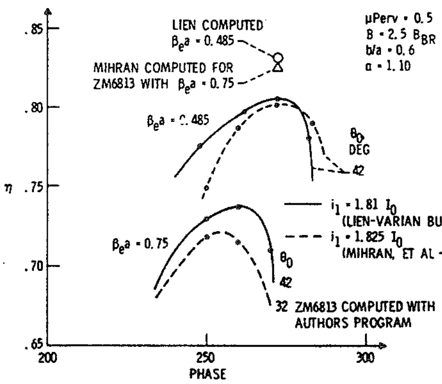

Fig. 6. Internal conversion efficiency computed with authors program for General Electric and Varian high-efficiency designs.

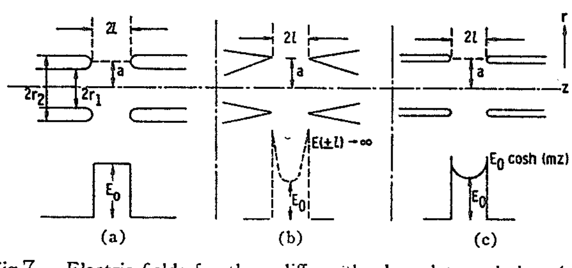

Fig. 7. Electric fields for three differently-shaped tunnel tips. (a) Constant field (E_0 = constant at $r = a$); blunt tips and relatively

TABLE I

Comparison Between Measured Efficiencies and Interceptions for a Varian Design

$i_1 = 1.81\ I_0$; $\beta_e a = 0.485$; μperv $= 0.5$

α	Measured (Lien) η	Measured (Lien) percent	Authors' Computed η	Authors' Computed percent
1.08	0.751	1.9	0.775	1.5
0.953	0.705	1.6	0.709	0.5
0.903	0.681	1.4	0.679	0

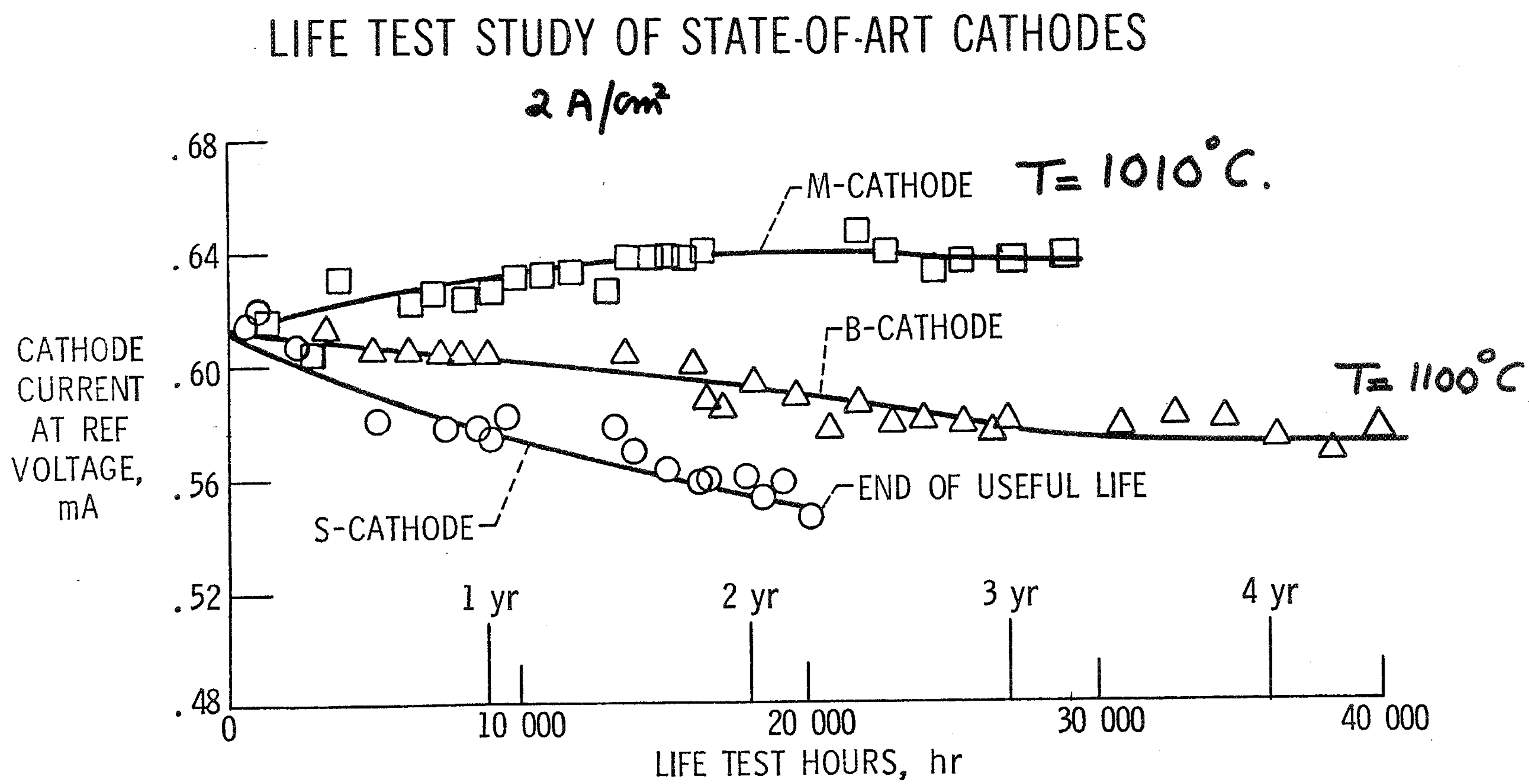

Fig. 8. Life Test Study of State-of-Art Cathodes.