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CROSSED-FIELD NOISE STUDIES: GUNS AND TRANSDUCERS

by

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ABSTRACT

Noise measurements are reported for two different kinds of guns which are of importance for crossed-field amplifiers, the short Charles type and the short Kino gun. Forward-wave noise figures are presented as a function of the beam position between the sole and circuit electrodes and of degree of space-charge limitation. This work continues the previously reported low noise-figure measurements previously reported for a backward-wave amplifier. Using the results of these measurements and the small signal theory, the beam fluctuation quantities at the output of the gun are estimated.

The use of velocity jumps in a drift region of a crossed-field amplifier as noise transducers to reduce the noise figure has been proposed. The boundary conditions for an ideal jump are presented. An analysis is done to determine the transformation of beam quantities through a jump. The possibility of noise reduction is discussed.

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I. INTRODUCTION

This paper covers two phases of noise studies on crossed-field electron streams. The first phase is concerned with noise-figure measurements on a forward-wave crossed-field amplifier. The electron streams for interaction are derived from two types of short guns, namely the Kino gun and the Charles gun. A method of determining the beam fluctuation quantities at the gun exit plane is proposed and used to estimate these beam noise parameters for the guns mentioned above. Estimates on a theoretical model are also presented. The other phase of the work is a detailed study of the effect of a velocity jump as a noise-transducing mechanism. The possibility of noise reduction is discussed.

II. NOISE MEASUREMENTS

These are performed on a linear-beam device with the electron gun mounted on a platform that can be moved up and down. Hence the beam can be injected at different levels between the sole and circuit electrodes. At the same time, of course, the potentials are adjusted so that the beam always flows straight in the interaction region upon leaving the gun. This is the same amplifier structure for which we have previously reported the 10.5 db noise figure when operated as a backward-wave amplifier.[1] The present work uses the amplifier in the forward-wave mode since it is felt that the objective of determining the noise quantities at the gun exit plane can be readily realized through the less complicated analysis of a forward-wave amplifier.

Following Gould's analysis,[2] which takes account of only two beam waves in the interaction region, the noise electric field at the output of the amplifier can be expressed in terms of ac surface charge density $\sigma_1(o)$ and beam position fluctuations $y_1(o)$ at the input plane of the interaction region. This is written as:

$$E_N \equiv E_{ex} = A \cdot \sigma_1(o) + B \cdot y_1(o) \qquad (1)$$

where A and B are related to the interaction parameters and the beam position between sole and circuit electrodes. Defining the noise figure in the standard form as the ratio of signal-to-noise ratio at the input to that at the output of the amplifier, we obtain the expression for noise figure F as

$$F = 1 + \frac{|E_{ex}|^2}{|E_{th}|^2} \qquad (2)$$

where $|E_{ex}|^2$ is the squared absolute value of the excess noise electric field at the output due to the beam fluctuations, and $|E_{th}|^2$ is the thermal noise output resulting from the Johnson noise at the input.

Substituting (1) in (2) and rearranging in the form of a matrix we get

$$(F - 1)_i = \begin{bmatrix} P_{i1} & P_{i2} & P_{i3} & P_{i4} \end{bmatrix} \begin{bmatrix} \overline{\sigma_1^{2}(o)} \\ \overline{y_1^{2}(o)} \\ \mathrm{Re}\,(\sigma_1(o) \cdot y_1^{*}(o)) \\ \mathrm{Im}\,(\sigma_1(o) \cdot y_1^{*}(o)) \end{bmatrix} \tag{3}$$

where $\overline{\sigma_1^{2}(o)}$, $\overline{y_1^{2}(o)}$, $\mathrm{Re}(\sigma_1(o) \cdot y_1^{*}(o))$, and $\mathrm{Im}\,(\sigma_1(o) \cdot y_1^{*}(o))$ are respectively the mean square values of $\sigma_1(o)$, $y_1(o)$ and the real and imaginary parts of correlation between them. P_{i1}, P_{i2}, P_{i3} and P_{i4} are related to the parameters A and B at the beam position designated as "i". For four independent beam positions, i = 1, 2, 3, 4, we can form a square array corresponding to four different values of noise figure F_1, F_2, F_3 and F_4. Now, the noise quantities are given as

$$\begin{bmatrix} \overline{\sigma_1^{2}(o)} \\ \overline{y_1^{2}(o)} \\ \mathrm{Re}(\sigma_1(o) \cdot y_1^{*}(o)) \\ \mathrm{Im}(\sigma_1(o) \cdot y_1^{*}(o)) \end{bmatrix} = \begin{bmatrix} P_{11} & P_{12} & P_{13} & P_{14} \\ P_{21} & P_{22} & P_{23} & P_{24} \\ P_{31} & P_{32} & P_{33} & P_{34} \\ P_{41} & P_{42} & P_{43} & P_{44} \end{bmatrix} \times \begin{bmatrix} F_1 - 1 \\ F_2 - 1 \\ F_3 - 1 \\ F_4 - 1 \end{bmatrix} \tag{4}$$

which can be easily determined by measuring noise figure at three independent beam positions for which the matrix elements can be estimated.

The results of noise figure measurements are shown in Fig. 1 for two types of short guns. The results for the Kino short gun and the Charles gun are shown by the solid and dotted lines respectively. Also shown in the figure for general information is the available power gain for the forward wave operation at f = 1500 Mc. Now we choose any four points from the noise figure curves and using Eq. (4), obtain the beam fluctuation quantities at the input to the circuit. The results of these calculations are incomplete at the time of the writing.

Some additional experimental data is shown in Fig. 2. This figure shows a considerable noise smoothing with space charge for both guns at this operating frequency of 1500 Mc. Since the short Kino gun and the Charles gun are specifically designed for incipient space-charge-limited and temperature-limited operations, these experiments seem to confirm space-charge smoothing for well focused electron streams from short guns. This is also in agreement with the recent theoretical results obtained by M. A. Pollack,[4] R. P. Wadhwa,[5] and R. Y. C. Ho.[6]

III. VELOCITY JUMP

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III. VELOCITY JUMP

In the second phase of this work we consider the possibility of putting a velocity jump in the drift region preceding an amplifier structure. The idea is based on an analogy with previous work done with space-charge waves in the O-type beams. At first thought, it may appear that the velocity jump would effect only cyclotron waves, and since these couple little with the circuit in the space-charge wave amplifier, nothing much could be achieved in this way. However, it turns out that a detailed study of the conditions at the jump indicates that there is a coupling among the cyclotron and space-charge waves which may be of significance in reducing the noise figure. In this phase of the work we use the four-wave model for the drifting region and velocity jump, and the five-wave model for the interaction region. The accelerating portion of the beam shown at the left side of Fig. 3 is treated as mentioned above by using the modified Llewellyn-Peterson equations.[7] Then at the π plane, a projection of these beam fluctuations is made into the direction of the beam and normal to it. Beyond that, the beam is treated as a drifting stream up to the point where the velocity jumps are inserted. The jump may be either up or down in velocity, of arbitrary magnitude excepting of course practical matters such as defocusing the beam. Two jumps are applied one-quarter cyclotron wavelength apart and the dc potential returns back to the value before the velocity jumps. Then, there is the amplifier portion at the last part of beam model. These transformations are shown in matrix form under the block diagram. We see that the noise quantities at the cathode are operated on by a series of matrices representing each of the blocks to obtain the output noise.

The scheme for a jump is to adjust the electrode potential such that the beam jumps in velocity, but that the fields are such as to keep it moving straight. The boundary conditions at one edge of the jump region, plane 1-1', shown in Fig. 4 have been derived assuming the distribution of dc electric field to be described as a unit-step function at the idealized narrow gap. The boundary conditions are

$$v_{yb} = v_{ya}\,, \qquad y_{1b} = y_{1a}$$
$$U_{zb} + \phi_b = U_{za} + \phi_a\,, \qquad I_{zb} = I_{za} \tag{5}$$

where v_y and y_1 are ac velocity and ac displacement in the y-direction, respectively, U_z and I_z are a kinetic potential $(v_{oz}\, v_{1z})$ and total current in the z-direction, respectively, ϕ is an ac potential given by the product of y_1 and dc electric field, the subscripts a and b indicate the quantities just before and after the jump. The correctness of these boundary conditions can be shown by substituting them in the equations for conservation of energy and kinetic power.

Using the conditions twice at the plane 1-1' and 2'2', we obtain the transformation matrix of the pair of velocity jumps shown in Fig. 5:

$$\begin{bmatrix} \dfrac{\sigma_{1d}}{\sigma_{oa}} \\[2ex] -\dfrac{v_{zd}}{u_{oa}} \\[2ex] -j\dfrac{v_{yd}}{u_{oa}} \\[2ex] -y_{1d} \end{bmatrix} = \begin{bmatrix} 1 & -\frac{1}{r}\left(1+\frac{j}{mr}\right) & \left(-j-\frac{1}{mr}\right) & \left(\frac{1}{r}-1\right)\left(1+\frac{j}{mr}\right)\beta_{ma} \\[2ex] -j\,u_{oa}\left(\frac{DS}{u_o C}\right)_b r^3 & -\left(\frac{1}{r}-1\right) & -j & \left(\frac{1}{r}-1\right)\beta_{ma} \\[2ex] -u_{oa}\left(\frac{DS}{u_o C}\right)_b r^2 & -\frac{j}{r} & 0 & j\left(\frac{1}{r}-1\right)\beta_{ma} \\[2ex] 0 & -\frac{1}{r\beta_{ma}} & -\frac{j}{\beta_{ma}} & \frac{1}{r} \end{bmatrix} \begin{bmatrix} \dfrac{\sigma_{1a}}{\sigma_{oa}} \\[2ex] -\dfrac{v_{za}}{u_{oa}} \\[2ex] -j\dfrac{v_{ya}}{u_{oa}} \\[2ex] -y_{1a} \end{bmatrix}$$

in which r is velocity jump ratio (u_{ob}/u_{oa}); $m = (\omega_c/\omega)$, σ_o and σ_1 are $\rho_o t$ and $\rho_1 t$, t is a beam thickness, ρ_o and ρ_1 are dc and ac charge densities respectively, u_o is dc velocity in the z-direction, β_{ma} is given by ω_c/u_{oa}, C is $\coth\beta_e a$, which is same as in Gould's paper,[2] DS is the same notation as in Gould's paper. The subscripts d and a indicate the quantity just after plane 2-2' and before plane 1-1', respectively, and b is between the velocity jumps. The matrix relates beam fluctuating quantities, that is, charge density, velocity components, and ac beam position on one side of the jump to those corresponding quantities on the other side of the jump. This is the matrix J which was shown in the matrix product of Fig. 3 indicating how the calculations would be made. We have also worked out the mode theory for the velocity jump and we have obtained the mode amplitudes after the jumps in terms of the amplitudes before the jumps. The transformation matrix in terms of the mode amplitudes has nonzero off-diagonal terms which show that there is a coupling among the cyclotron waves and the space-charge waves. This is of significance in reducing the noise figure of the space-charge wave amplifier, since it shows we can transfer the noise quantities of space-charge waves to the cyclotron waves.

We have calculated the noise power output resulting from cathode fluctuations with a quarter-wave velocity-jump region. We have allowed a drift of arbitrary length so that the velocity jump may be positioned at the best point on the standing wave. The result of these matrix multiplications is the electric field due to noise quantities at cathode. The absolute square value is given by

$$|E_{1z}|^2 \propto 16.2 + 37.1R^4 - 44.4R^2 - (8.87R^3 - 5.30)\sin(\beta_m Z + 69.3^\circ)$$

$$+ 0.530R^2 \sin^2(\beta_m Z + 69.3^\circ) \qquad (7)$$

where $R = [(1/r) - 1]$ and $\beta_m Z$ is a measure of the position of the jump in the standing cyclotron-wave pattern. To evaluate this equation, we have substituted the practical values used in our experiment. We notice that the fourth and fifth terms are small compared to the rest of the terms which indicates that the noise figure is insensitive to the position of the jump. It appears that the noise figure of space-charge wave amplifier is much more dependent on the ac displacement than the ac velocity. For the simplicity in evaluating the expression we set $\beta_m Z + 69.3^\circ = 90^\circ$. Fig. 5 shows the effect of changing the jump ratio r. We see that there is a several db reduction at optimum r for the numerical values used. At present it may be said that the velocity jump does appear to be capable of modifying the noise output. However, it should be pointed out that the theory for the transformations through the gun is not yet adequate for confidence about the quantitative validity of the results.

REFERENCES

1. N. R. Mantena and T. Van Duzer, "Noise figure calculations and measurements of a backward-wave amplifier," Study of Crossed-Field Amplifiers, Final Report, University of California, Berkeley, Electronics Research Laboratory, Series No. 60, Issue No. 493; February 1963.

2. R. W. Gould, "Space-charge effects in beam type magnetrons," J. Appl. Phys., Vol. 28, No. 5, pp. 599-605; May 1957.

3. T. Van Duzer, "Noise-figure calculations for crossed-field amplifiers," IEEE Trans., Vol. ED-10, No. 6, pp. 370-378; November 1963.

4. M. A. Pollack and J. R. Whinnery, "Noise transport in the crossed-field diode," IEEE Trans., Vol. ED-11, No. 3, pp. 81-89; March 1964.

5. R. P. Wadhwa and J. E. Rowe, "Monte Carlo calculation of noise transport in electric and magnetic fields," IEEE Trans., Vol. ED-10, No. 6, pp. 378-388; November 1963.

6. R. Y. C. Ho, private communication; August 1964.

7. T. Van Duzer, "Transformation of fluctuations along accelerating crossed-field beams," IRE Trans., Vol. ED-8, No. 1, pp. 78-86; January 1961.

8. A. Sasaki and T. Van Duzer, "Study of crossed-field amplifiers," Final Report, University of California, Berkeley, Electronics Research Laboratory, (Addendum), pp. 52-95; February 1963.

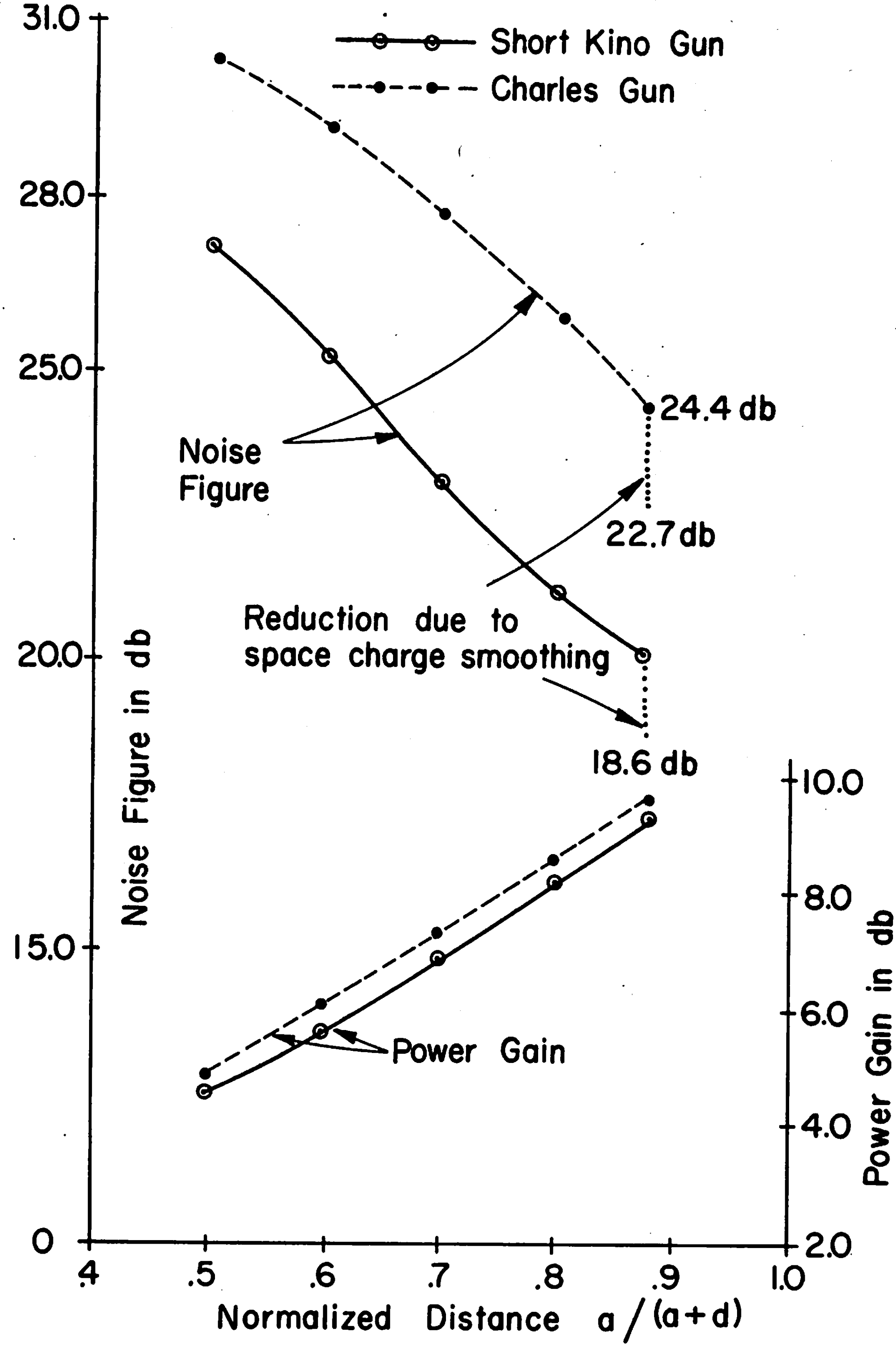

Fig. 1. Variation of noise figure and power gain with normalized beam distance.

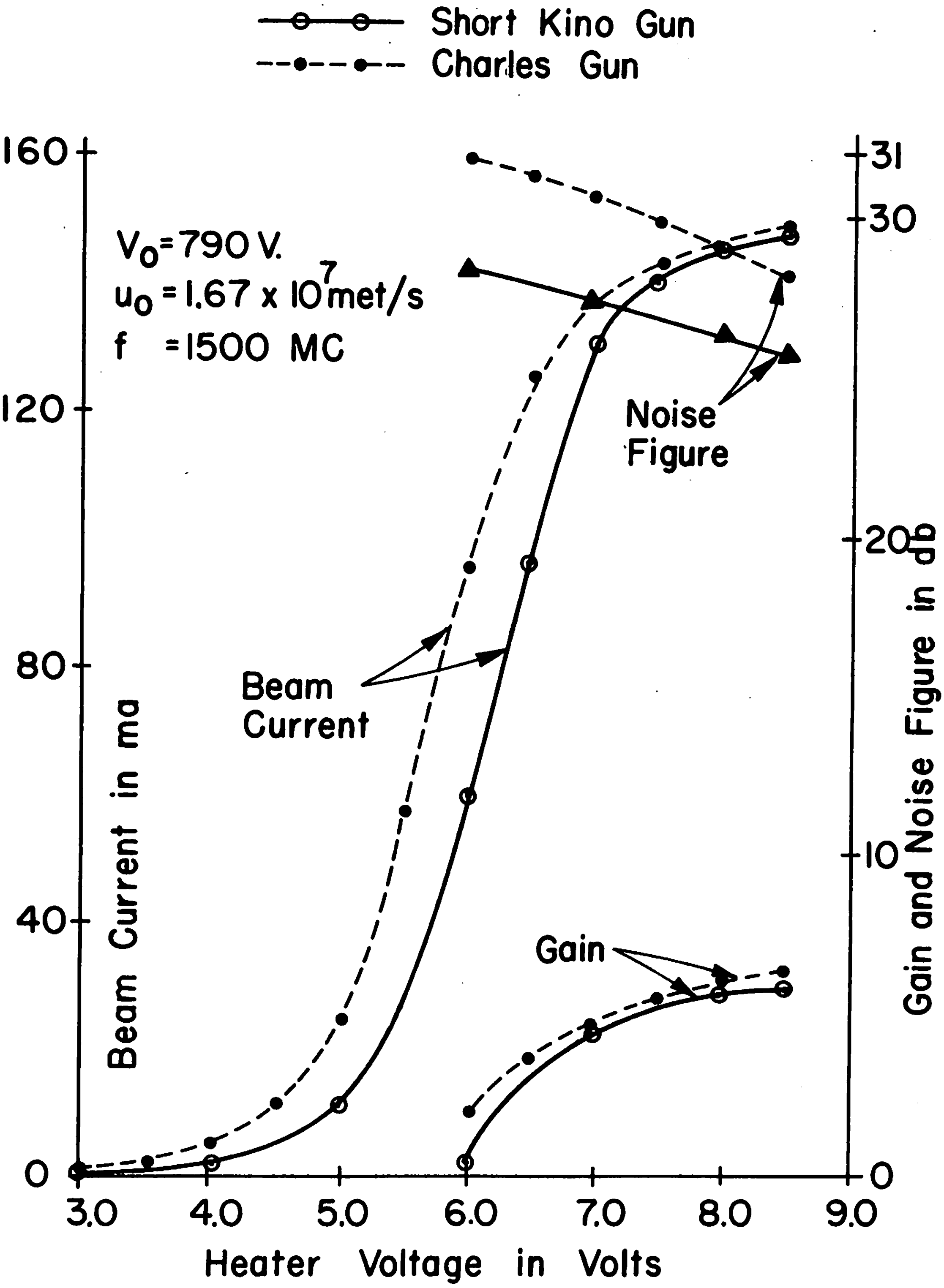

Fig. 2. Experimental results showing the space-charge smoothing.

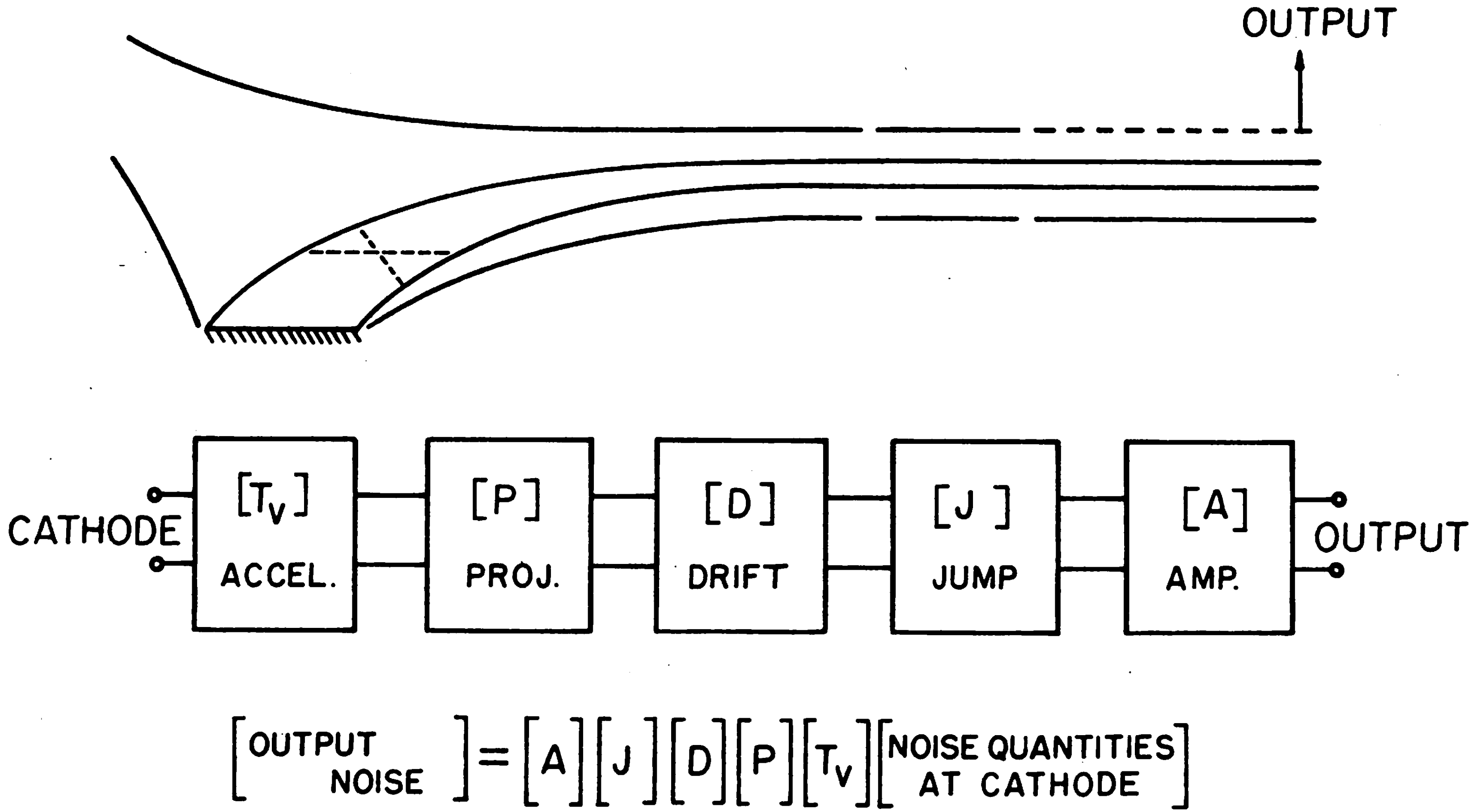

Fig. 3. Model for evaluation of noise figure with velocity jump.

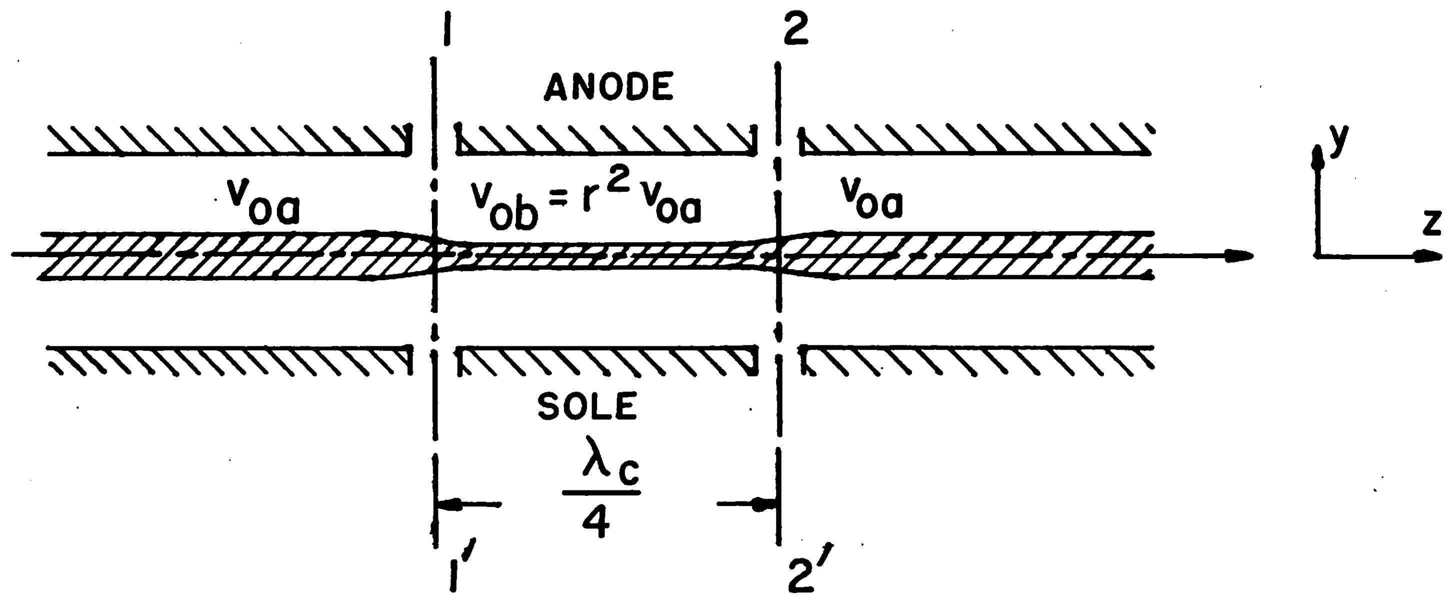

Fig. 4. Velocity jump in the drift region of a crossed-field tube.

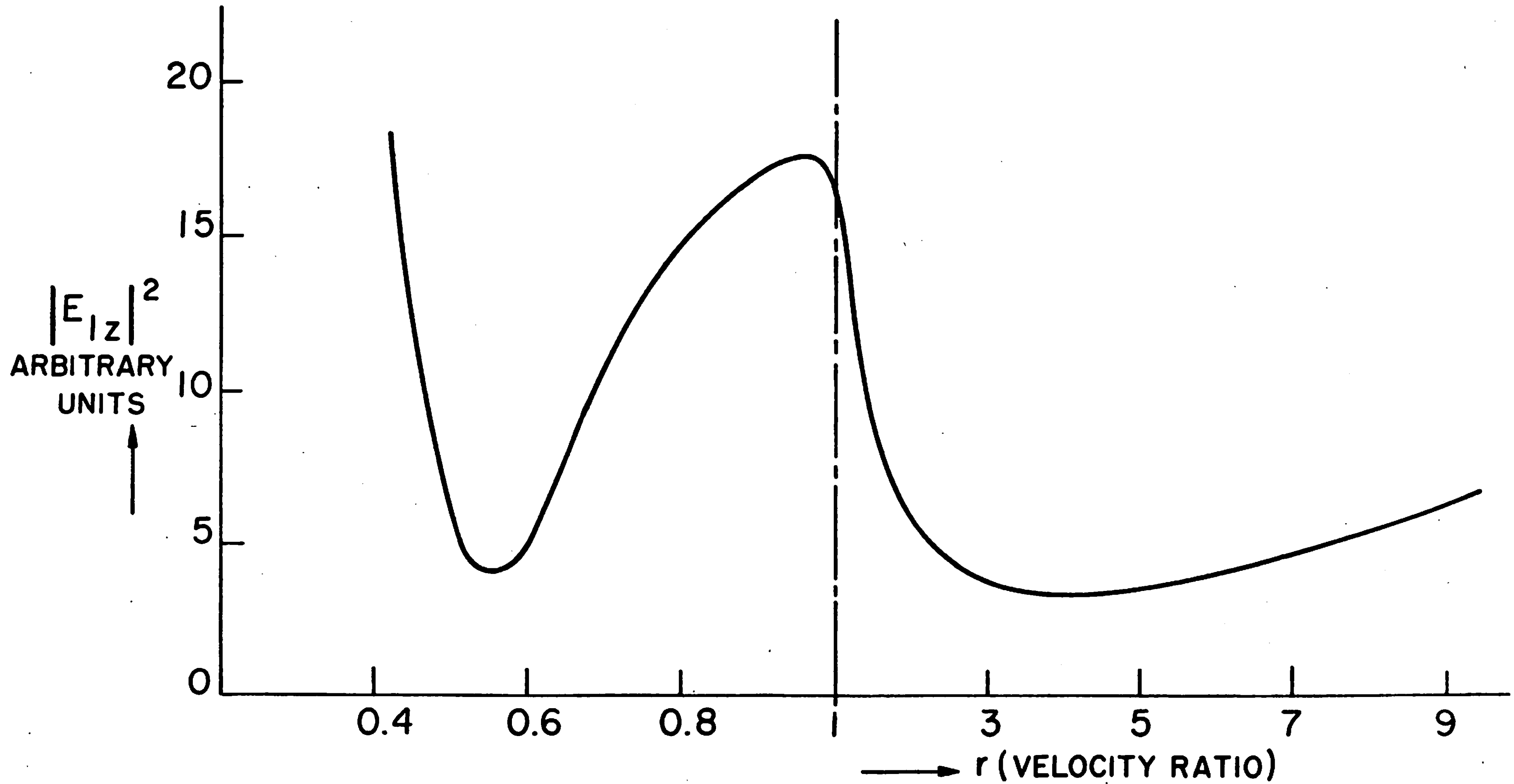

Fig. 5. Noise power as a function of the velocity jump ratio, r.