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INVESTIGATION OF RF NOISE GENERATION FROM SPACE VEHICLES

Quarterly Report No. 5
Contract NAS 8-862

Prepared by: Robert D. Wanselow

24 July 1962 through 24 October 1962

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I. INTRODUCTION

This report presents the results of work carried out at the Hughes Research Laboratories during the period 24 July 1962 through 24 October 1962 on the measurement of rf noise generation by a high-beam-density electrostatic ion engine. The program is being supported by NASA Contract NAS 8-862.

The primary objective of this program is to determine analytically and experimentally the power spectrum of noise generated by electrical propulsion devices, with emphasis on the cesium ion engine being developed at Hughes under NASA Contract NAS 5-517. This information is important for the design of flight test telemetry and space vehicle communication systems which require a minimum of interference with onboard and ground-based receivers.

Previous work under this contract included an analytical determination of noise generated in neutralized ion beams by various mechanisms. In addition, investigations were made on a typical annular ring cesium ion engine over the frequency range of 38 to 2200 Mc. The tests yielded no measurable noise output from the ion beam itself, although rf radiation as a result of low level periodic arcing across the engine insulators was observed. It was concluded that the noise output from the ion beam would be below typical receiver noise levels in all cases considered.

This report summarizes the experimental as well as analytical work during the past report period. The results of tests made on a Penning engine and the analytical study of noise growth mechanisms on an ion beam indicate that noise interference to receivers aboard future electrically propelled spacecraft will probably exist if the receiver carrier frequency is located near the electron plasma or cyclotron frequencies. (See Appendix.)

II. DESCRIPTION OF EXPERIMENTS

Two different types of engines were investigated, the Penning discharge engine and the annular ring cesium ion engine. All testing was performed in the cylindrical metallic test chamber described in the previous report. Investigations were performed in the frequency range of 38 to 2200 Mc by employing a stub antenna for rf reception inside the test chamber.

The annular ring cesium ion engines investigated had a designed perveance of 160 and 202 npervs, respectively. In an effort to obtain data on engines operating at higher current densities, the higher perveance ring engine was operated at 5.4 kV with a current density of about 9.9 mA/cm^2 and a beam density of approximately 7 x 10^9 ions/cm^3. This 0.71-kW beam had considerably more power with increased density over the beams investigated during the previous quarter. The 160-nperv engine had a neutralizer; however, the beam of the 202-nperv engine was neutralized by external gas within the chamber.

During the past period texts were initiated on an electron bombardment (Penning) engine operating with xenon. The engine was tested under four beam current conditions ranging from 25 to 200 mA. The current densities of these engine tests were less than those of the cesium ion engines because of the much large exhaust area employed.

III. EXPERIMENTAL RESULTS

A. Ion Engines

As reported previously for earlier engine designs, an arcing pheromenon around insulator terminals existed and produced a noise spectrum from 90 to 300 Mc. However, with an improved engine design there was no measurable noise power observed on either of the annular ring engines tested.

The higher perveance engine did not have a neutralizer; however, the 160 nperv engine did. This engine was tested over a neutralizer current range of 0 to 125 mA. No noise power was observed as a function of the neutralizer current in any of the tests because the predominant neutralizing agent probably comes from the residual gas within the chamber.

B. Penning Discharge Engine

The Penning engine was observed under four different operating conditions. All of the pertinent engine parameters are summarized in Table I for each of four beam current conditions. It can be seen that the calculated and measured rf radiation at the electron cyclotron frequency agree within 6%. Noise peaks were also observed at the electron plasma frequency; however, agreement between theory and measurement is rather marginal for the 100 and 145 mA cases. Some of the calculations for the 25 mA case have been deleted because the magnetic field was not measured. In addition to the above described noise, a few other noise peaks were observed over the spectrum. (See Fig. 1.) This phenomenon is unexplainable at the present time but will be investigated further in the next report period.

These preliminary measurements indicate that the Penning engine can be expected to radiate noise in the frequency spectrum near the electron cyclotron frequency and possibly near the electron plasma frequency. Experimental investigations to date indicate that the Penning engine will probably generate a great deal more noise interference for space communications receivers than the cesium ion engine.

TABLE I

PENNING ENGINE NOISE RADIATION DATA

Beam Current, mA	Voltage, kV	Magnetic Field, G	Density, ions/m^3 x 10^{15}	Calculated Cyclotron Frequency, Mc	Nearest Measured Radiation Peak, Mc	Calculated Cyclotron Oscillation Power, dBm/Mc	Measured Cyclotron Oscillation Power, dBm/Mc	Calculated Plasma Frequency, Mc	Nearest Measured Radiation Peak, Mc
25	3.5	N.A.[a]	0.422	--	--	--	--	184	195
100	5.0	160	1.405	448	450	-80	-97	336	250
145	4.5	72	2.150	202	190	-87	-95	415	300
200	5.8	64	2.610	179	185	-88	-93	456	450

[a] Not available.

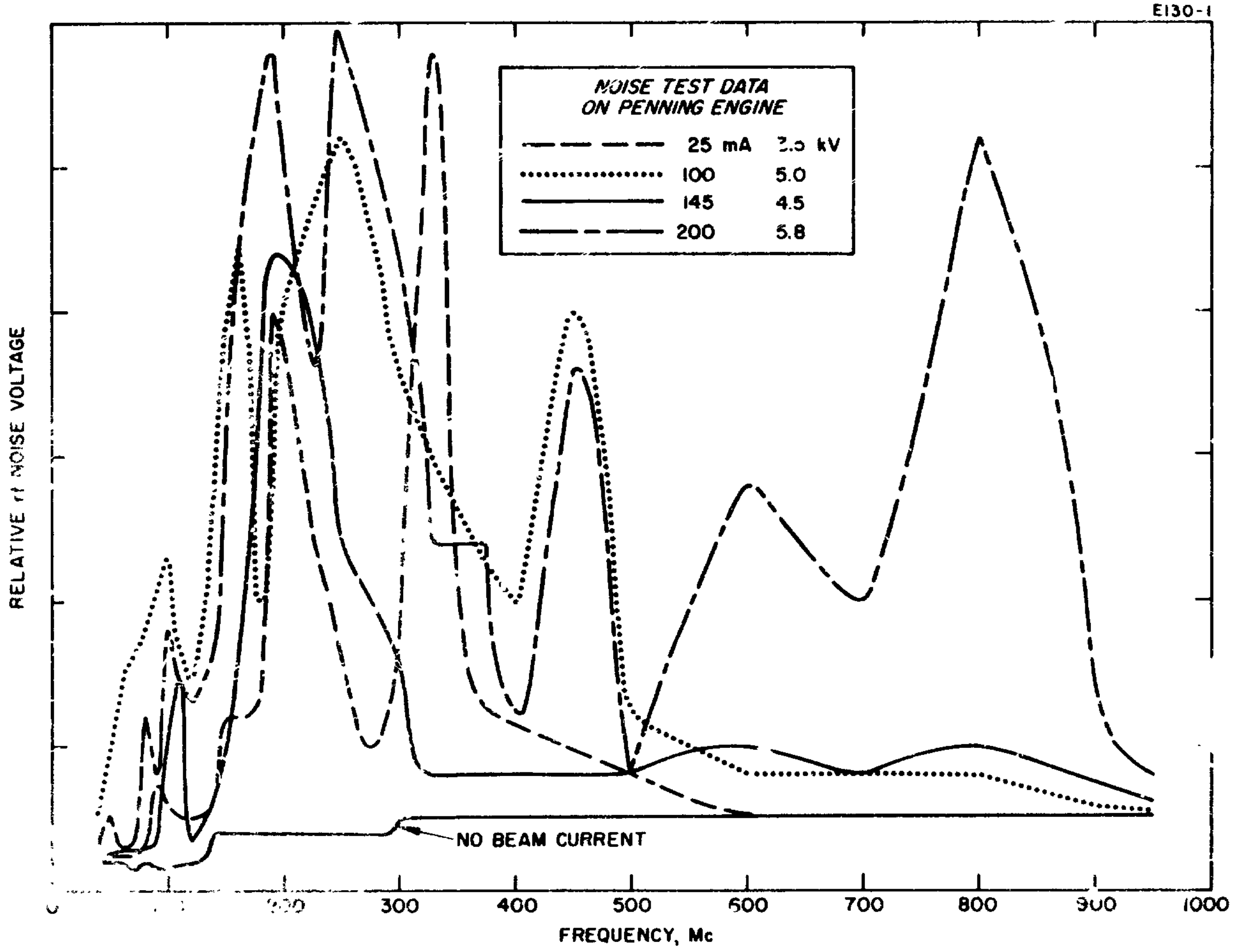

Fig. 1. Noise test data on Penning engine.

IV. CONCLUSIONS

Investigations to date on cesium ion engines have exhibited no noise from the ion beam in the 38 to 2200 Mc spectrum. However, initial tests of a Penning engine have exhibited noise radiation in the vicinity of the electron cyclotron frequency and the electron plasma frequency. In addition, analytical studies of a possible noise growth mechanism in a narrow band about the electron plasma frequency do indicate that it may be possible to generate rf interference. Therefore, communications systems should probably be operated above the cyclotron and plasma frequencies. In this higher frequency range there is a definite reduction in plasma noise, and the conductive properties of the plasma will have less effect on antenna patterns.

V. PLANS FOR NEXT PERIOD

During the next quarter more data will be obtained on noise generation in the 38 to 2200 Mc band. Efforts will be made to perform tests during neutralizer operation under pulsed beam conditions. If available, engines with higher currents and particle densities will be investigated.

Additional tests will also be made on the Penning engine with emphasis on noise radiation as a function of the magnetic field and other pertinent engine parameters.

APPENDIX – RF NOISE GROWTH RADIATION FROM A NEUTRAL ION BEAM

The plasma beam ejected from most ion engines consists of essentially monoenergetic ions and of electrons with a spread of velocities. A double stream instability may develop, the exact nature of which depends on the precise form of the electron velocity distribution relative to that of the ions. In the simplified plasma model considered, conditions near the exhaust plane of a typical cesium annular ring ion engine can exhibit this instability; hence, an rf growth of noise may develop. The instability can cause maximum amplification at the electron plasma frequency with a decreasing level of broad-band wave growth as the frequency separation below the plasma frequency is increased. Above the plasma frequency the noise growth drops off very rapidly with frequency.

As shown by Louisell and Pierce,[1] power flow in plasma beam devices exists in two forms of energy – kinetic and electromagnetic. If one considers a conventional plasma in which all the displacement current is in the same direction as the convection current, then there will be no net current flow in this direction because of the capacitive effect of the space-charge flow. That is, the displacement current will have an opposite sense to the convection current due to the restoring force effect by the space-charge field. Therefore, H will be zero and, if the electric field generated by the conversion of longitudinal wave energy of bunched charges is purely longitudinal, the electromagnetic power flow, i.e., the Poynting vector, will be zero. This is the condition of the ion beam downstream from the engine exhaust plane, which renders it unfavorable for rf noise radiation. In addition, conditions along the ion beam far downstream are also unfavorable for the existence of instability growth phenomena. This is because the probable thermal velocity distributions of the ions and electrons are superimposed to the extent that the composite velocity distribution does not exhibit the double peaked characteristic shape necessary for the well known double stream growth mechanism.

When the beam diameter is of the order of a plasma wavelength or less, however, as will be the case in the vicinity of the engine exhaust plane, the plasma stream of space-charge waves appears as a linear source of multiple oscillating dipole charges aligned in the direction of charge flow. This effect exhibits a relatively strong directional field transverse to the beam with a negligible component parallel to the beam; hence, the longitudinal component of the displacement current is negligible. Therefore, since the displacement and convection currents are not equal, electromagnetic power can flow in the form of a surface wave along the plasma outer surface. The following equations and calculations are based on this line of reasoning.

A. RF PROPAGATION

For electromagnetic power to flow or propagate it is necessary that the subject waves possess a Poynting flux. This requires that the electric field contain a component transverse to the direction of propagation. Hence, the presence of a transverse dc magnetic field or the beam spreading mechanism of the neutralizing electrons within the exhaust plasma of an ion engine might couple the motion of the longitudinally oscillating charge into a direction perpendicular to the longitudinal field and the propagation vector. This transport phenomenon would then exhibit a transverse component of the longitudinal electric field. Feinstein and Sen[2] have shown that the ratio of these field intensities in the presence of a static magnetic field may be approximately equated as follows:

$$\frac{E_{\text{transverse}}}{E_{\text{longitudinal}}} \cong \left(\frac{v_z}{c}\right)^2 \left(\frac{\omega_c}{\omega}\right) , \qquad (1)$$

where

v_z ≡ electron velocity in the longitudinal direction

c ≡ velocity of light in vacuum

ω_c ≡ cyclotron radian frequency corresponding to the applied magnetic field

ω ≡ radian frequency of the propagating rf disturbance

The case with no static magnetic field (as with the ion engines under study) but with a component of mass velocity transverse to the direction of wave propagation gives rise to a corresponding motion on the part of the bunched charge which serves to generate a transverse electric field. The ratio of these field intensities may be approximated as follows[2]:

$$\frac{E_T}{E_L} \cong \left(\frac{v_y v_z}{c^2}\right) = k\left(\frac{v_z}{c}\right)^2 , \qquad (2)$$

where

v_y ≡ κv_z transverse component of the electron velocity

k ≡ proportionality constant

The average electromagnetic power S radiated from the outer surface of the plasma in the direction of beam flow may be equated as follows:

$$S = \frac{1}{2} E_T H_T = \frac{1}{2} \frac{E_T^2}{Z_o} , \qquad (3)$$

where Z_o is the characteristic wave impedance of free space. For the ion engines to be considered in this analysis, it will be assumed that there is no dc magnetic field present. Hence, by combining (2) and (3) a general relationship for the rf power radiated as a function of the longitudinal space charge fluctuation field may be stated as follows:

$$S = \frac{1}{2} \frac{k^2}{Z_o} \left(\frac{v_z}{c}\right)^4 E_L^2 \quad \text{watts/unit area} . \qquad (4)$$

Equation (4) indicates that only a very small fraction of the longitudinal fluctuation field energy may be converted into electromagnetic radiation, since for nonrelativistic beams $v_z/c \ll 1.0$ and for most engines $k < 1.0$.

B. NOISE GROWTH

In the previous discussion (4) was derived with no emphasis as to whether the longitudinal field E_L exhibited growth. When the value of the relative velocity between ions and electrons in a hot plasma exceeds a certain limit, instability may exist, and growing longitudinal space-charge waves may occur.[3] As the relative velocity is increased beyond this threshold of instability, the growing waves occur first at long wavelengths since the velocity is small.[4] However, exponentially growing waves cannot exist unless the derivative of the composite velocity distribution of the charged plasma particles has more than one zero. This is the well known two-stream growth mechanism. Hence, for the purpose of discussion it can be assumed that the ions are stationary relative to the low-energy neutralizing electrons with velocity v_z; the wavelength $2\pi/\beta$ of the fluctuations and their frequency ω (possibly complex) obey the simplified dispersion relation

$$\frac{\omega_{pi}^2}{\omega^2} + \frac{\omega_{pe}^2}{(\beta v_z - \omega)^2} = 1 \quad , \tag{5}$$

where ω_{pi} and ω_{pe} are the ion and electron radian plasma frequencies, respectively. In an effort to simplify the mathematical solution, eq. (5) is written with the assumption that the electrons are monoenergetic. This assumption may be justified since the velocity distributions of the ions and electrons are well separated. From this equation, the growth rate of longitudinal fluctuations maximizes at the electron plasma frequency, i.e., when $\beta v_z = \omega_{pe}$, as shown by Buneman.[5] The initial coulomb field fluctuation energy will therefore build up exponentially to the level of the directed drift energy. This energy growth will be of a local nature provided the ions and electrons are drifting in the same direction. The initial longitudinal reference coulomb field may be related as follows[6]:

$$E_o = 1.44 \times 10^{-7} (N)^{2/3} \quad , \qquad (6)$$

where N is the electron density. Therefore, the longitudinal field magnitude of the growing oscillation may be obtained from the following:

$$E_L^2 = E_o^2 e^{\tau} \quad , \qquad (7)$$

where the growth factor of the fluctuation energy is defined as[6]

$$\tau = \left(\frac{1}{A}\right)^{1/3} \delta \frac{z}{\lambda_p} \qquad (8)$$

and

A ≡ mass number of the ions

λ_p ≡ plasma wavelength

z ≡ distance downstream which encompasses the local growth disturbance

δ ≡ characteristic root of the dispersion equation signifying gain

Substitution of (7) into (4) yields a final relationship for the amount of rf power radiated by a surface wave generated by a noise growth mechanism. This electromagnetic power then becomes

$$S = \frac{1}{2} \frac{k^2}{Z_o} \left(\frac{v_z}{c}\right)^4 E_o^2 e^{\tau} \quad . \qquad (9)$$

Appreciable growth will be exhibited in a relatively narrow frequency band about the electron plasma frequency with quite a noticeable selectivity effect occurring with a corresponding increase in growth. This is graphically illustrated in Fig. 2 for two drift conditions — over distances of 10 and 50 plasma periods. Space permitting, the fluctuation energy can be built up to the level of the drift energy. At this level the maximum growth factor τ_{max} of the fluctuation energy becomes[6]

$$\tau_{max} = 3 \ln \left[20(A)^{2/9} \frac{E}{E_o}\right] \quad , \tag{10}$$

where E is the externally applied field. Thus, the maximum rf power radiated becomes

$$S_{max} = \frac{1}{2} \frac{k^2}{Z_o} \left(\frac{v_z}{c}\right)^4 E_o^2 \, e^{\tau_{max}} \quad . \tag{11}$$

C. APPLICATION

A quantitative calculation of the expected rf radiation from an annular ring cesium ion engine will be made in the vicinity of the exhaust plane. In Fig. 3 a model sketch of the ion beam geometry near the exhaust plane is shown. Two examples of rf radiation will be considered, first in the vicinity of the neutralizer electrode and then on the exit side of the exhaust plane. The engine tested was designed for a perveance of 160 npervs. The following are some of the pertinent engine parameters necessary in calculating the electromagnetic radiation:

f_{pe} = 640 Mc
N = 5×10^{15} ions or electrons/m^3
v_z = 1.325×10^6 m/sec
λ_p = 0.207 cm

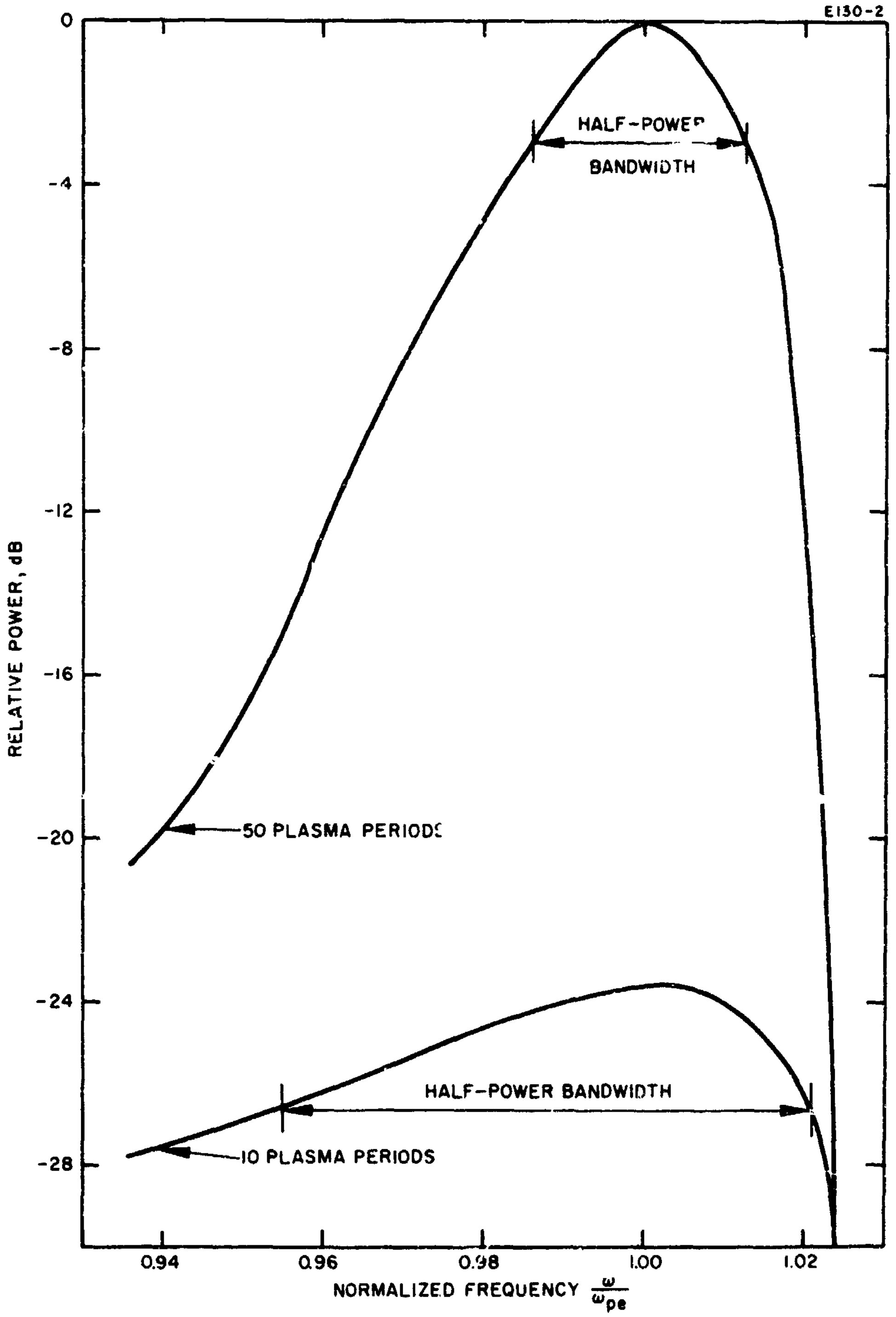

Fig. 2. Relative growth curves as a function of the local drift distance.

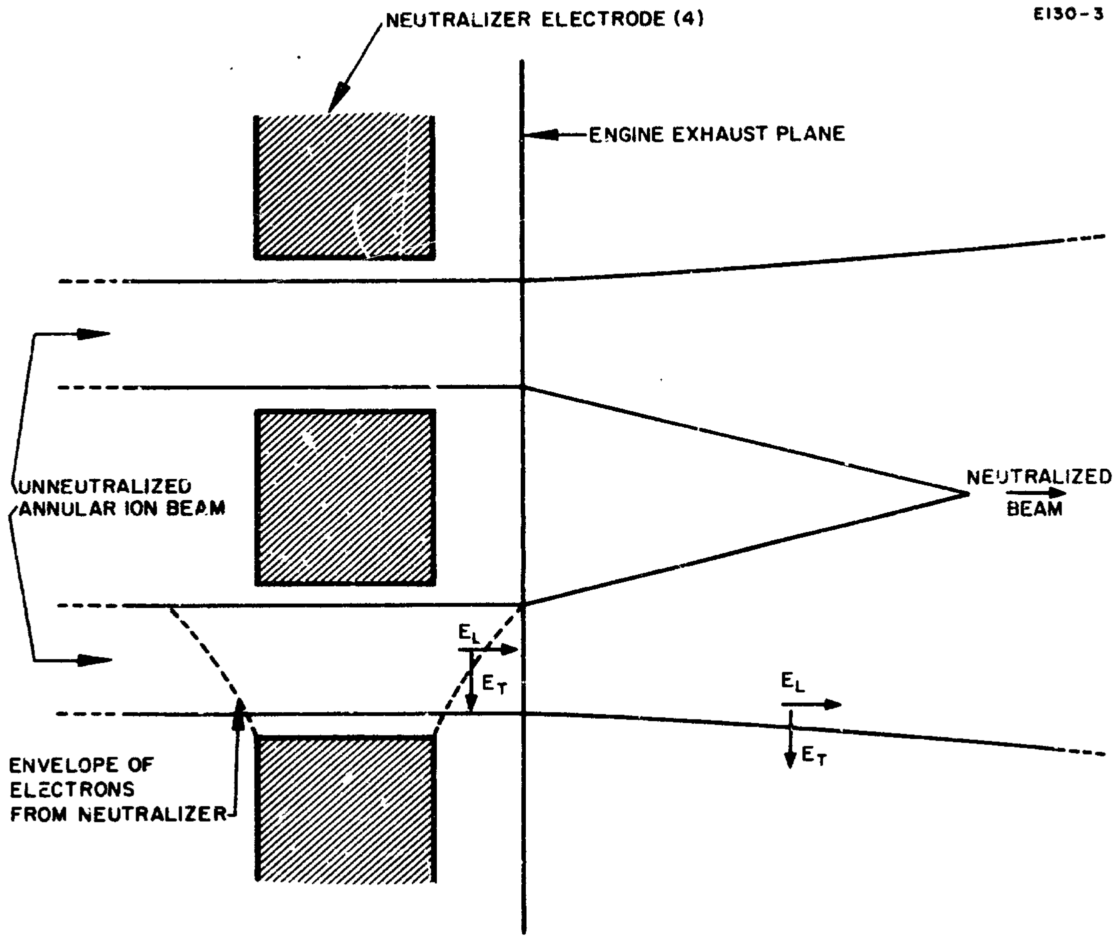

Fig. 3. Sketch of ion beam geometry model in vicinity of engine exhaust plane.

$E_o = 4.26 \times 10^3$ V/m

$Z_o = 377\Omega$

$k = 0.5$ for the thermal electrons

In the neutralizing region, electrons will be dispersed quite rapidly in the ion stream near each of four electrodes. If the cross-sectional area of the generation of the surface wave is assumed to be approximately one debye wavelength deep at the periphery of the coaxial beam near each of the four electrodes, then the radiated electromagnetic power from (9) becomes approximately -80 dBm at the electron plasma frequency of 640 Mc. However, at frequencies displaced more than 5% from the plasma frequency, the power level has dropped below -85 dBm. Also, since this source of rf radiation comes from within the engine, there will be a certain amount of isolation between this directed radiation and the receiving antenna aboard the space vehicle. Hence, the noise power level (due to the growth mechanism in the electrode region) at the ship's antenna would probably be -100 dBm or less in the vicinity of the plasma frequency.

In the region external to the plasma engine the beam diameter no longer will appear as a thin stream in terms of plasma wavelengths; hence, no electromagnetic power will be able to propagate as previously discussed. In addition, the thermal velocity distributions of the ions and electrons probably will be superimposed such that the two stream growth mechanism cannot exist. That is, the double peaked composite distribution will not be easily defined. However, if by some disturbance or perturbation the growth of energy can exist and propagate, the maximum radiated electromagnetic power from (11) would be approximately -34 dBm also peaked at the same electron plasma frequency. This local growth would occur over about 58 plasma wavelengths along the beam. However, at frequencies more than 5% displaced from the plasma frequency the power level would be below -60 dBm.

D. SUMMARY

The theory presented for the rf generation from a noise growth mechanism on the ion beam indicates that electromagnetic radiation within a neutralized beam will appear over a relatively narrow bandwidth about the electron plasma frequency. This condition can exist if the velocity distributions of the ions and electrons are sufficiently separated that the composite velocity distribution exhibits a double peaked characteristic; this condition may possibly be realized if the ions are assumed to be relatively stationary with respect to the low energy electrons. However, it should be noted that the theory developed here does not take into account the electron velocity distribution but rather has assumed that the electron velocity is single valued. This velocity distribution is not at all well known in present plasma engines.

In the examples given, the results indicate that this type of rf noise would probably interfere with present day space communications receivers which operate with wide open front ends in the vicinity of the electron plasma frequency. However, receivers with command decoder circuits operating with some form of modulation coding probably would not be affected by any beam noise present as long as the selected receiver carrier frequency is different from the plasma frequency.

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