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CALIFORNIA INSTITUTE OF TECHNOLOGY

ELECTRON TUBE AND MICROWAVE LABORATORY

VACUUM TUBE RESEARCH PROJECT

QUARTERLY STATUS REPORT NO. 4

January 1, 1954 to March 31, 1954

A REPORT ON RESEARCH CONDUCTED UNDER

CONTRACT WITH THE OFFICE OF NAVAL RESEARCH

VACUUM TUBE RESEARCH PROJECT

CALIFORNIA INSTITUTE OF TECHNOLOGY

Pasadena, California

QUARTERLY STATUS REPORT NO. 4

January 1, 1954 to March 31, 1954

Prepared under Contract Nonr 220(13)

Task Order No. 13

for

Office of Naval Research

Submitted by: Lester M. Field.

QUARTERLY REPORT

Nonr 220(13)

Vacuum Tube Research Project

California Institute of Technology

This report covers the fourth three months of operation under this contract and is for the period January 1, 1954 through March 31, 1954. It describes progress made on the problem of saturation under attenuators with particular reference to the comparison of our work with some of the measured results on a tube being tested at the Hughes Aircraft Company.

Perhaps the principal content of this report is a survey of theoretical papers in radio astronomy which forms the beginning of our research effort to determine the relative merit of these various possible explanations of radio generated noise, and may include an attempt to devise our own theory of some radio generated noise.

Further work on the bifilar helix for the possible production of a backward-wave oscillator which will require no magnetic focusing fields is also described. The report also discusses the beginning of a research activity on the M-carcinotron and theoretical research programs with respect to all of the above.

Project A - Theoretical Studies of the True Tape Helix and Application to Electrostatically Focused Bifilar Backward-Wave Oscillators

Staff: R. W. Gould, R. D. Weglein, L. M. Field.

Performance of the bifilar backward-wave oscillator tube has been improved to the point where approximately 10 milliamperes can be transmitted to the collector out of 12 milliamperes admitted current, with the order of 500 volts on one helix and 1500 volts on the other. Oscillation has been observed in a small number of discrete bands under essentially these conditions. A new tube is now under construction in which it is hoped that internal matches will provide a smooth oscillation characteristic. Further measurements are being held up pending completion of this tube.

Project B - Backward-Wave Oscillator Efficiency

Not active during the period reported here and will be reactivated only after good backward-wave oscillator performance is observed on Project A.

Project C - Power Limitation in Forward Gain Amplifier Tubes by Attenuator Saturation

Staff: W. Buchman, T. Feuchtwang, L. M. Field

This report will present further considerations of the effects of attenuators on the high level operation of traveling-wave tubes. Some experimental results pertaining to the theoretical considerations will be presented.

The usual traveling-wave tube increasing wave mode is not one of the modes which is capable of existing in an attenuator region. Therefore, it is necessary to know how new modes are excited in such a region. One assumption which has been made to advantage in our initial studies is that the attenuator region can be considered as if it were merely a drift space. Under such simplification it has been shown that the modes that will be excited in the attenuator will scramble and cause high current peaks which are much larger, typically by a factor of about four than the I_o component of the current at the end of an attenuator.

The ideas presented in the previous reports have been applied to the high power probe tube built by the Hughes Aircraft Company to be described at the 1954 Electron Tube Research Conference. The results show that mere consideration of the attenuator as a drift space which causes space charge waves with differing space charge wavelengths to be set up--taking care to include those set up by the initial velocity modulation of the increasing wave--does not predict saturation at a level low enough to agree with the experimental results. For such a high power tube to saturate at the observed levels, there must be some kind of a gain process taking place in the attenuator region. This gaining process may be some form of admittance wall amplification using the attenuator coating as the wall. There was a discrepancy of approximately a factor of three in current which had to be made up by this gaining process. Reasonable assumptions about probable resistance-wall amplification under this attenuator as taken from the Birdsall and Whinnery work* seem to give just about a factor of three in current amplification as required. It also may be true that the helix is interacting with the electron stream even though there is a heavy attenuator present. The exact nature of the process which is taking place is the subject of our current study.

The postulated process for saturation of the Hughes high power tube is now as follows. An increasing wave is incident upon the attenuator. The wave in the electron stream continues to grow by one of the mechanisms postulated above. The circuit wave, however, is absorbed by the attenuator. By the time the electrons leave the attenuator section, the wave on the beam has grown so large that it has saturated. This saturated beam now has to set up a circuit wave on the helix. It is then obvious that the circuit wave can never be expected to reach a level as large as the one which would

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* Birdsall and Whinnery, Journal of Applied Physics, 24, pp. 215-323, 1953.

be obtained if the beam were not saturated at the exit of the attenuator.

Now perhaps it may be worthwhile to consider the conditions which determine whether the effects of high order modes or the amplification under the attenuator is of importance in determining attenuator effects at high level. High power tubes are made to have large current densities. This means that the plasma frequency is relatively high, $\omega_\rho/\omega = 0.2$ or greater. This high plasma frequency means that there are a sufficient number of plasma wavelengths in the length of an attenuator so as to give considerable gain as an impedance wall amplifier or a traveling-wave tube with attenuation.

For smaller powers, the probe tube that was tested here at the Institute recently is an example of the opposite situation. The plasma frequency is relatively low, $\omega_\rho/\omega = 0.04$. This means a practical attenuator is only a fraction of a plasma wavelength long. This precludes the possibility of having large gains available in the attenuator region. One should realize that what is considered as a plasma wave can also be considered as a sum of two traveling waves of slightly different propagation constants which interfere with each other in space. In an admittance wall amplifier, one of these waves becomes an increasing wave and the other a decreasing wave. If the gain is not large, the amplitudes of the two waves are still almost equal and can interfere with each other to a sufficiently great extent so as to behave almost like plasma waves. This is what appears to happen in low current density tubes.

One further distinction between high and low current density tubes should be made clear. $C\frac{\beta_e}{\beta_\rho}$ is large for low current density tubes ranging about one or two, and small for high current density tubes down to as low as 0.3 . In the first case, velocity modulation at the input of the attenuator gives rise to large current peaks in the current profile near the end of the attenuator due to high order modes, whereas in the second case the contribution of initial velocity modulation to current peaks at the end of the attenuator is quite small indeed. This can be understood by referring to equation (9) of our Quarterly Status Report No. 2 .

The above argument leads to the following conclusion. For low current density tubes the attenuator causes large peaks to be built up in the ac current profile of the beam due to initial velocity modulation. These peaks are many times the size of the useful signal, and cause saturation to occur before the signal can saturate the beam. This process has been described in a previous report. For high current density tubes, some kind of gain process is occurring in the attenuator with the result that at relatively low drive levels a saturated beam may leave the attenuator. This saturated beam must then set up an electromagnetic wave upon the structure.

At present, plans are being made to extend the work of Chu and Jackson* to include the effects of a conductance sheath around the helix. In this manner, one can follow how the principal propagation constants change with the parameters of the problem. Such an analysis could put much of the previous discussion on gain under the attenuator on a rigorous basis.

As a simplification to the problem for the present, and not unimportant by itself, the following situation is being studied. One follows the Chu and Jackson analysis exactly up to the point of setting up the boundary conditions. It is then assumed that there is no conduction across the helix, but that there is finite surface conductivity along the helix. This means that tangential electric field is continuous both along and across

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* Chu and Jackson, "Field Theory of Traveling-Wave Tubes", Proc. I.R.E, 36, 853-863 (1948) .

the helix. Current flows along the helix in proportion to the electric field in that direction. This means that the tangential magnetic field difference between the inside and outside of the helix in the direction across the helix is equal to this surface current density. The magnetic field along the helix is continuous.

One can then determine the circuit admittance of Chu and Jackson, Y_r. Then, by use of the beam admittance, which has been calculated by Birdsall and Whinnery, the propagation constants can be determined, and the effect of changing surface conductivity can be studied.

The next extension would be to consider a lossy wall which is separate from the helix. The same procedure will apply.

During this period of study there has been set up a high-gain low-power tube in our laboratory with a moveable probe system which can measure field intensity on the helix as a function of position along the helix for various drive conditions and with various attenuator configurations. A number of measurements have been taken with this tube and they are being compared with our theory to this point. It appears that we can predict the drive level at which saturation occurs for various lengths of attenuators as well as predict the onset of other non-linear phenomena such as decreased gain after the attenuator. Presentation of such probe measurements will be made in the next report.

Project D - Proposed Method of Expansion of Traveling-Wave Tube Fields into Modes.

Staff: W. Buchman, L. M. Field.

In our previous report, No. 3, some ideas about the expansion of traveling-wave tube fields into modes were expressed. The problem that presents itself is that of how to determine the amplitude of each mode that is excited.

It may be that the Poynting vectors for the various modes form an orthogonal set. Such a property must be true for any structure for which the energy propagation can be computed as the sum of the energies as if only one mode were present at a time.*

Another way of approaching the problem of achieving orthogonal modes, is through the concept of transforming to principal coordinates. This is the same as transforming the energies, electric and magnetic, to quadratic forms. In the case of lossless systems, this should always be theoretically possible.

One case which is simple to describe is that of a stretched string which is supported at its ends by elastically bound massive points.

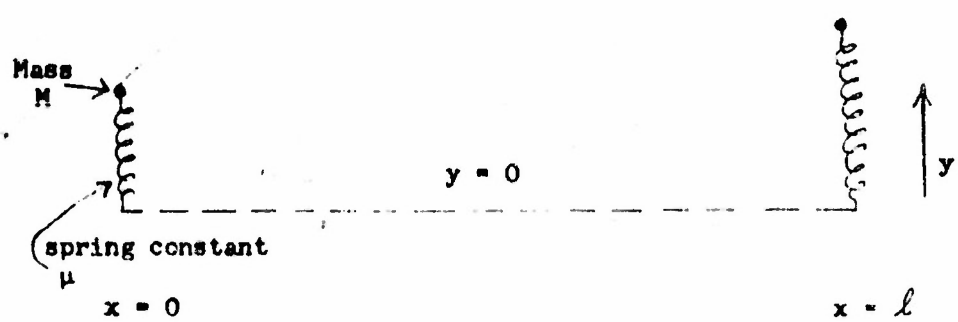

Figure 1.

ρ = linear mass density of the string

If $y(x)$ is the displacement of the string, possible modes are

$$g_i = (\nu_i \sin m_i x + \cos m_i x)\cos(m a t - \varepsilon)$$

where $\tan m_i \ell = \dfrac{2\nu_i}{1-\nu_i^2}$, $\nu_i = \mu - \dfrac{M a^2 m_i^2}{m T_1}$

* R. B. Adler, "Waves on Inhomogeneous Cylindrical Structures", Proc. IRE, 40, 339-348, (1952)

In this case, the orthogonality of the modes is expressed as

$$\rho \int_0^{\ell} (\nu_r \sin m_r x + \cos m_r x)(\nu_s \sin m_s x + \cos m_s x)\, dx$$

$$+ M + M\,(\nu_r \sin m_r \ell + \cos m_r \ell)\,(\nu_s \sin m_s \ell + \cos m_s \ell) = 0$$

$$\text{for} \quad r \neq s$$

Note particularly, that the last two terms denote the energy of the end points. The use of the function between 0 and ℓ is not sufficient.* Perhaps some of the considerations of Rayleigh are applicable in modified form to the traveling-wave tube.

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* J. W. S. Rayleigh, "Theory of Sound", Vol. I, 200-202. (Dover Pub.), New York, 1945).

Project E - A Study of the Relation between Microwave Noise Generation Processes and Possible Noise Generation Processes in Radio Astronomy.

Staff: R. W. Gould, L. M. Field.

In order to study the relation between microwave noise processes and those which occur in radio astronomy, we first made a review of the literature on this topic. Following this review of the literature we have begun an examination of methods which can distinguish those suggested processes which are physically reliable from those which are not. A report of our progress in finding such methods will be given in our next report.

A Short Summary of a Review of the Literature on the Theory of Non-Thermal Noise Generation in the Sun

At wavelengths below one meter and down to as low as one centimeter radio noise is observed from the sun, much of which is attributable to the temperature of the sun in its various layers. This thermally generated noise is relatively well understood with the exception of small minor disagreements with the optical data which are now being satisfactorily adjusted. There are, however, a variety of types of noise which are probably not thermal in origin and which are distinguished from each other by their duration, polarization and variation in spectrum with time. These are tabulated and connected with their probable optically visible origin in "The Sun".[1]

It seems reasonable that different processes in the sun account for these different types of noise in view of their different polarization and duration characteristics. We will here concentrate upon the possible theoretical explanations of what may be one of the simplest of these phenomena by attempting to understand the randomly polarized noise associated with solar flares. In these solar flares matter--probably ionized--is obviously rushing through portions of the sun's atmosphere which contain relatively stationary ionised particles and we will attempt to find a noise generation process somewhat akin to those which occur in mocrowave vacuum tubes. Unfortunately, it is quite likely that the velocity of transport of the ions is much below the mean thermal velocity of the relatively stationary medium at the temperatures at which they find themselves, and hence appreciable extensions of any present microwave noise generation theories are required.

Our search of the literature covering these matters begins with an article by J. R. Pierce[2], in which he examined the effect of a stream of electrons moving through a region of stationary ions and found infinite gain for a frequency of excitation equal to the ion plasma frequency unless collisions among ions existed or the ions had a finite drift velocity. He also found that in the presence of a magnetic field growing waves could exist near the cyclotron frequency. He did not suggest any application of his paper to noise generation in the sun's atmosphere, however, nor was his theory particularly applicable to the case in which the average drift velocity was comparable to the thermal velocities of the ions.

In 1949, Dr. A. V. Haeff published an article[3] on the growing wave possible when two streams of slightly different velocities traverse the same space, and in the same year Dr. J. R. Pierce wrote an article[4] along similar lines.

One of the first suggestions that these ideas might be applied to conditions for noise generation in the solar atmosphere was made by Dr. Haeff.[5] Haeff postulated two streams existing in the sun's atmosphere with a mean velocity approximately that determined from the length of time it takes for a solar disturbance to cause effects in our own atmosphere. He chose the velocity difference between the two streams to be that appropriate to the temperature existing in the outer layers of the sun, and he chose a density for his streams which is essentially that of the electron density near the sun's surface. As a result he was able to predict a spectrum which agrees roughly with that determined by observations. Unfortunately, as numerous critics of this tyeory have pointed out, the process described is highly suggestive of what may be happening, but the model is somewhat too arbitrary and at odds with a variety of known conditions in the sun. For example, Bailey[6] complains that the Haeff theory uses values of current density and mean velocity which are off by a factor of 10^6 from allowable values determined by other means. In addition he observes that no mechanism for the radiation of the energy is described and little attention is paid in the theory to the precise layers in the sun's atmosphere at which the interaction is supposed to take place or to the well-known effects of absorption, refraction and reflection of these layers on radio emission.

At about the same time, Bailey published a series of articles[7] proposing an electro-magneto-ionic theory in which he analyzed waves that propagate in two ionized gases moving relative to each other with a magnetic field present. Here the magneto-ionic theory of Appleton which has been reasonably well confirmed in our own atmosphere, predicted cut-off waves, and Bailey obtained complex roots for these cut-off waves--and then suggested that growing and decaying waves were therefore possible. The suggestion was then made but not followed in detail, that these growing waves might well account for some of the solar flare noise generation. Much doubt has been expressed with respect to the physical interpretation or possibility of excitation of these solutions, first by Walker and then by Twiss. Walker's comments relate initially to an error with respect to the inclusion of relativistic effects at one point in the analysis and their exclusion at another point. Bailey later corrected this difficulty[8] but criticism of the interpretation of the solutions remained. In essence this criticism relates to the ease with which apparent growing-wave solutions may be found in a cut-off system and the great difficulty of determining whether or not such growing waves can be excited and can extract appreciable amounts of energy from the streams and convert these energies into growing waves. The waves that Bailey studied are "transverse" waves and the energy in them is primarily electromagnetic as contrasted with the "longitudinal" waves studied by Haeff and Pierce. Their energy is primarily electrostatic and kinetic or inertial. This circumvents the radiation problem, the energy is already primarily electromagnetic so no conversion is needed.

Associated with these articles by Bailey, there appeared an article by Roberts[9] on wave amplification in which he applied some of Bailey's ideas to traveling-wave tubes and arrived at the novel consequence that a circuit of the sort used in traveling-wave tubes was not necessary and that an electron stream inside of a cut-off waveguide could have a phenomenal growth rate. This wave was evidently a cut-off wave looked at from the wrong end as several authors pointed out[10,11] and is not excitable from the small amplitude end. Bailey's cut-off waves in his electromagnetic ionic theory are much more difficult to definitely rule out, and by setting up very artificial impedance boundaries, it is conceivable that some small energy exchange might exist. However, it appears highly questionable that such properties would exist in the sun.

Several workers[13,14,15] have considered the motion of a thermal plasma in a uniform static magnetic field. Malmfors[13] worked on the problem first but Gross[14] has pointed out that his solution is in error. Gross found that if the plasma has a sharp distribution of particle velocities in a plane transverse to the static magnetic field there are gaps in the frequency spectrum, the width of the gap depending on the velocity at the peak of the velocity distribution function. This is thought to give rise to total reflection of an incident wave, when the frequency lies within one of these bands. Sen[15] has examined Gross' result in more detail and found that the dispersion relation may be satisfied by complex frequencies, the interpretation being that disturbance in certain bands of frequency can grow exponentially with time. Both Gross and Sen have considered the wave number to be real and Sen finds that this wave number must exceed a certain minimum in order for complex frequencies to be possible. These treatments suffer from the common difficulty that boundary conditions are not included.

In any event, the situation is sufficiently complicated that we will turn for the time being at least, to solutions in the abrence of a magnetic field and hope that at least some of the noise from the sun--for example, the randomly polarized noise from solar flares--can be explained without the necessity for a magnetic field to produce polarization effects. Most of the work which has been done in this direction and which we are currently attempting to extend, appears in the works of Feinstein and Sen[16], Sen[17], and the many papers of Bohm and collaborators.[18]

In addition to these articles, Ryle[20] criticizes all the non-thermal theories proposed up to that time, principally those of Haeff and of Bailey on the basis that the radiation could not escape from the sun at the levels at which it was contemplated that those processes take place. Second, that these processes contained no mechanism for radiation. Third, that velocity modulation cannot exist in a region with a high relative temperature. Fourth, that the streams proposed would come apart before they got to a region where they could radiate. Most of these criticisms do not apply to the theories which were proposed later in which all of these points are carefully considered.

Twiss[21] in a recent article, suggests a completely new mechanism in which a klystron-like action occurs with transverse waves in the ionized region and two discontinuities in the sun's atmosphere acting in essence as buncher and catcher resonators. Unfortunately, it is difficult to verify the possible existence of such discontinuities and for the moment, at least, we will concern ourselves with noise sources on which more observational information is available.

Feinstein and Sen[16] have analyzed the double stream case assuming that one stream is at rest but has a thermal velocity spread. They find complex propagation constants are possible even when the moving stream has a velocity much less than the mean thermal velocity of the particles of the stream which is at rest. This result is interpreted as making amplification possible under these circumstances, a result which is in disagreement with the results of Bohm and Gross.[18] The latter have found that only particles or a stream of particles whose velocities are greater than the mean thermal velocity of the stationary stream excite its plasma oscillations. There has as yet been no careful examination of whether the complex propagation constants found by Feinstein and Sen represent growing waves and can be excited under ordinary circumstances. We propose to investigate this point much further. In their paper, Feinstein and Sen also consider that radiation might be produced by transverse motions induced by a static magnetic field.

Using an analysis quite similar to the preceding one, Sen[17] has estimated the density and motion of solar material associated with a solar flare by fitting the spectrum observed by Wild.[19] It is assumed that decrease in frequency of the noise is due to a motion of its source into regions of lower plasma frequency. The velocity which the moving stream is required to have is, however, only about a tenth the mean thermal velocity of the electrons in the corona, so the result is subject to the criticism that it is in disagreement with Bohm and Gross.[18] In addition, the mechanism of radiation is not discussed, except to point out that it need not be very efficient (in terms of the kinetic energy of the injected particles.)

It should be noted that in this article by Sen[17], a square thermal velocity distribution is used which leads to certain analytical difficulties as pointed out by Twiss[22] and Landau[23]. The correct thermal velocity distribution may be carried through however, and leads to essentially the same waves which were interpreted by Sen as a possible amplification mechanism. This interpretation needs further study as previously discussed, and may be another case of a disguised cut-off system. Nevertheless, the approach is very suggestive of further analysis which may be productive and is the first detailed paper using realistic solar conditions and a fairly detailed analysis.

For the near future, our interests will be in the directions of resolving the Bohm and Gross vs. Sen discrepancy, examining the interpretation of Sen's growing waves to determine if a true amplification process exists, examining the effect on these longitudinal plasma waves at a discontinuity or boundary in ion density to determine the resulting radiation, and later examining some of the more likely plasma excitation processes such as those treated by Bohm and Gross to find other possible models for noise generation in the absence of magnetic field.

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Project F - A Study of the M-Carcinotron

Staff: J. W. Sedin, L. M. Field

A review of the existing French and English literature on the M-carcinotron has been undertaken. Some discrepancies among the start oscillation formulae given in various of these articles was noted and in consequence of this, an attempt was made to derive the start oscillation current for the M-carcinotron using the parameters common in J. R. Pierce's book, Traveling-Wave Tubes.

The result of such analysis showed that Pierce's parameters could be reduced to those of, for example, the article in the British J.I.E.E.[1] which summarised the French work, if ϕ and ϕ' of Pierce's notation were evaluated for a typical structure. We are satisfied therefore that the start oscillation formula given there is correct, except that, as the French workers point out, the disagreement with experiment requires the inclusion of some additional interaction process.

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[1] Journal Inst. of E. E., November 1953, Part 3.

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