AD-A196 005

DTIC
ELECTE
MAY 1 8 1988
S   D

FINAL SCIENTIFIC REPORT

on

Contract AFOSR 82-0045

MILLIMETER MICROWAVE EMISSION BY USE OF
PLASMA PRODUCED ELECTRONS ORBITING
A POSITIVELY-CHARGED WIRE

November 15, 1983 to March 14, 1986

Igor Alexeff
Principal Investigator

88 - 10 180

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION Unclassified			1b. RESTRICTIVE MARKINGS	
2a. SECURITY CLASSIFICATION AUTHORITY			3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited	
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE				
4. PERFORMING ORGANIZATION REPORT NUMBER(S)			5. MONITORING ORGANIZATION REPORT NUMBER(S) **AFOSR-TR- 87-0432**	
6a. NAME OF PERFORMING ORGANIZATION University of Tennessee		6b. OFFICE SYMBOL *(If applicable)*	7a. NAME OF MONITORING ORGANIZATION AFOSR	
6c. ADDRESS *(City, State and ZIP Code)* Dept of Electrical Engineering University of Tennessee Ferris Hall, Knoxville, TN 37996-2100			7b. ADDRESS *(City, State and ZIP Code)* Bldg 410 Bolling AFB, D.C. 20332-6448	
8a. NAME OF FUNDING/SPONSORING ORGANIZATION AFOSR		8b. OFFICE SYMBOL *(If applicable)* NP	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER AFOSR-82-0045	

8c. ADDRESS *(City, State and ZIP Code)* same as 7b.	10. SOURCE OF FUNDING NOS.			
	PROGRAM ELEMENT NO. 61102F	PROJECT NO. 2301	TASK NO. A8	WORK UNIT NO.

11. TITLE *(Include Security Classification)* "MILLIMETER MICROWAVE EMISSION BY USE OF PLASMA PRODUCED ELECTRONS ORBITING A POSITIVELY-CHARGED WIRE" (U)

12. PERSONAL AUTHOR(S)

13a. TYPE OF REPORT FINAL	13b. TIME COVERED FROM 82/11/15 TO 86/03/14	14. DATE OF REPORT *(Yr., Mo., Day)*	15. PAGE COUNT 84

16. SUPPLEMENTARY NOTATION

17.	COSATI CODES		18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)* plasma, orbitron, microwaves
FIELD	GROUP	SUB. GR.	

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

Significant progress was recorded on the exploration of the physics of the Orbitron microwave source. Early, in the work, continuous emission was observed in the range up tp 26 GHz. A numerical code was developed for computing collective electron oscillations. Later, repeatable pulsed operation was observed up to 430 GHz at 0.2 watts in a two microsecond pulse. Spurious emissions up to 1000 GHz have also been observed.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☒ DTIC USERS ☒	21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED	
22a. NAME OF RESPONSIBLE INDIVIDUAL ROBERT J. BARKER	22b. TELEPHONE NUMBER *(Include Area Code)* (202)767-5011	22c. OFFICE SYMBOL NP

DD FORM 1473, 83 APR EDITION OF 1 JAN 73 IS OBSOLETE.

TABLE OF CONTENTS

Final Report

for

AFOSR Contract #AFOSR-82-0045

I. Background Information

This report describes a recently-completed program of research at the University of Tennessee's Plasma Science Laboratory. The contract research, which ran from November 15, 1983 to March 30, 1986, was performed at our laboratory which is located on the Knoxville campus, and is a part of the Electrical Engineering Department. Our laboratory has been specializing in research on new methods of microwave power generation, and a new fast opening plasma switch. These devices operate using electric field dominated plasmas and are unique in that no magnetic field is used. The plasmas in these devices exhibit several unique characteristics: narrow line, high frequency RF power emission; and strong radial electric fields, which have measured values which have been in the excess of several kilovolts per centimeter. Such electric field dominated plasmas can achieve high energy densities, and are of potential use in such applications as masers, pulsed broad-band radio frequency emitters, high power sub-millimeter microwave emission, communications and directed energy weapons.

The research supported in the past three years has produced four refereed journal articals, and fourteen conference papes at a funding level of

approximately $174,000 over the period from November 1983 to March 1986. Copies of these papers are included in Appendix A. The topics these papers cover include basic Orbitron theory, Orbitron experimental results, and a Magnetohydrodynamic model of the earth's magnetic field.

II. Objectives of Research

The contract running had one main objective and that was the development of the Orbitron Maser as patented by the principal investigator Dr. Igor Alexeff (see resume in Appendix B) in to a practical sub-millimeter oscillator and amplifier in the wavelength range from 10 mm-.1mm. The principal work was to be done by Dr. Alexeff, Fred Dyer (see resume in Appendix B), and various graduate assistants being supported by AFOSR.

The theory of the Orbitron and experimental data produced by the Orbitron suggested that this new type of maser is capable of operation at wave lengths smaller than .1 mm. During the course of experimentation we have found that millimeter and sub-millimeter radiation is easily generated without the need for bulky equipment, expensive magnets, or relativistic electron beams. We now routinely operate at wavelengths of .7 mm or less. Outlined below are the major goals achieved during each contract period.

November 1983 - October 1984

1. Narrow-Band, C. W. emission produced in the range 0-26 GHz.

2. The above emission lines have been fitted to cavity modes (except for that at lowest frequency).

3. The lowest mode (0.1-1GHz) has been identified as a plasmon (plasma excited).

4. Reliable pulsed operation at 2 mm now can be done.

5. A numerical code for computing collective electron oscillations in the system has been developed.

November 1984 - October 1985

1. Reliable pulsed operations have been extended to a wavelength of 0.7 mm - (430GHz) at 0.2 watts in a 2 usec pulse.

2. The device has been made <u>tuneable</u> in the centimeter range.

3. The efficiency in the centimeter range has been measured to be 5%.

4. A computational and analytic picture of 3-dimensional electron confinement around an etched wire has been produced.

5. A simple beam - line model of the maser has been developed and extended to a Vlasov (spread in orbit frequency) picture. The model predicts emission at harmonics of the orbit frequency.

6. A low frequency emission from ions was predicted and observed. The central wire was made negative so that ions, rather than electrons, orbit and exhibit negative mass instability.

7. A low level R.F. emission at low pressure was theoretically predicted and observed. This is produced by spontaneous instability of the electron ring.

8. R.F. emissions at a wavelength of 0.3 mm - (1000 GHz) have been observed.

November 1985 - March 1986

1. Steady-State emissions in a hard vacuum (1×10^{-6} Torr) was achieved using a hot filament for a electron supply.

2. Phase locking between multiple anode wires was predicted and experimentally proven.

3. Steady-State hard vacuum emissions proven to be externally tunable in the centimeter range.

4. Steady-State hard vacuum emissions proven to fit TEM cavity modes in the centimeter range.

5. The source of the earth's magnetic field predicted and experimentally shown from geological data.

III. Basic Concepts

The Orbitron Maser basically is an electrostatic millimeter wave oscillator. We compute that it can operat a free space wavelengths down to at least 0.1 mm. Limits in available magnetic field strength restrict conventional magnetic field devices to wavelengths above approximately 1.0 cm.

A basic form of the Orbitron Maser consists of a cylindrical cavity resonator with a wire running axially down its center (see Fig. 1).
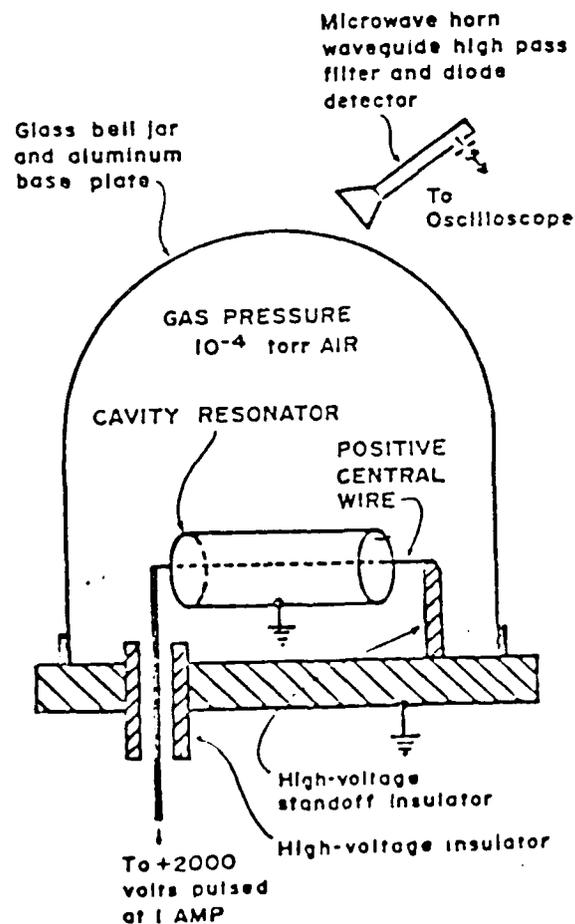

FIG. 1. Schematic of a typical microwave emitter. Microwaves are easily observed outside the bell jar at some distance, and can be focused, reflected, diffracted, etc.

6

This structure is then placed in a vacuum bell jar evacuated to about 10^{-4} torr. An end view of the maser, Fig. 2, shows that discharge-produced electrons are trapped in spiral precessing orbits. The standard beam-plasma treatment[1], adapted to
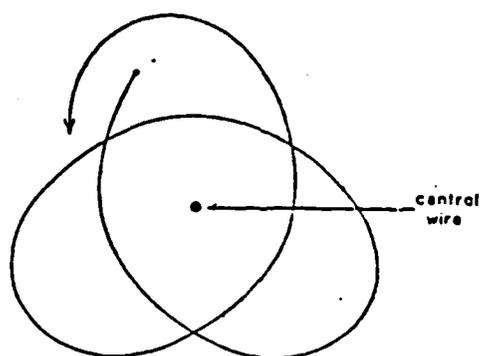

Fig. 2. End view of maser showing an electron with precessing orbit.

cylindrical coordinates, indicates that these spiralling electrons coupled to the cavity resonator will generate microwaves.

Our mathematical model is that a group of electrons, produced from a glow discharge, are each in a circular orbit with an initial angular frequency ω_0. The electrons do not interact with each other ($\omega_{pe} < \omega_0$) unless there is an external cavity field, here simulated by a resistive layer. If an electron clump occurs due to random fluctuations, it creates a local electric field that drags on image charge along in the resistive medium (simulating radiation resistance). The electron clump loses kinetic energy, moves inward in radius, increases in angular velocity, and overtakes more

slowly orbiting electrons ahead. Now the clump grows, the drag increases, and finally most of the electrons are swept up into a coherently rotating and emitting radial spoke. Since the electrons are moving at an angular velocity ω higher than their initial angular velocity ω_0, the emission occurs at a higher freuency than their initial orbital frequency ($\omega > \omega_0$). Since the power radiated by a group of coherently oscillating electrons goes as the square of the number of electrons, the power radiated can be large. In this preliminary calculation, electrons are assumed to be electrostatically trapped, hence ions would be electrostatically ejected and are not treated. In addition, since we suspect the action to occur close to the surface of the wire, only circular orbits ar treated.

In our work, a theoretical study of the instability was done first. The results are

$$\omega_0 = \frac{1}{r} \left(\frac{-Z_e e V_r}{m_e \ln(r_2/r_1)} \right)^{1/2} , \tag{1}$$

$$\omega + \omega_0 \pm \left(\frac{1}{\sqrt{2}} + \frac{i}{\sqrt{2}} \right) \omega_0^{3/2} \beta \tag{2}$$

$$\beta = \left(\frac{-Z_e e R n_e}{4\pi^2 V_r} \right) \omega_0^{3/2} \beta \tag{3}$$

In Eq. 1, ω_0 yields the angular frequency of rotation at radius r around a wire of radius r_1 charged to a positive potential V_r. $Z_e e$ is the sign and

magnitude of the electron charge, m_e is the electron mass, r_2 is the effective cutoff distance of the electric field. At low electron density, r_2 is the radius of the outer wall. Even if r_2 is not well defined due to increased electron density, it lies in a logarithmic term, and so is not a sensitive parameter. All units are MKS. A wire 1 mil. in radius (1/40 mm) and a voltage of 10 kV produces $\lambda \approx 1$ mm. Reducing the wire to 0.1 mil is reasonable (we have even smaller radius wires on hand), and so $\lambda = 0.1$ mm should be produced easily at V = 10 kV!

In Eq. 2, we find the emission frequency of an electron interacting with an external structure (the cavity). We find that if we choose a positive solution (gain), we obtain a real angular frequency somewhat above ω_o. Note that the growth rate peaks sharply at the highest possible value of ω_o, that for an electron just grazing the surface of the wire.

In Eq. 3, we compute the factor giving growth rate. Here, we simulate radiation resistance by placing our orbiting electrons between two resistive, concentric cylinders. Here, R is the resistance in ohms per turn, where $R \approx 2\pi r \rho (\ell \Delta r)^{-1}$. Here r is the average rdius of the two cylinders, ρ is the resistivity of the shell medium (Ω-meter), ℓ is the axial length of the cylindrical structure, and Δr is the sum of the thicknesses of the two cylinders. The number of electrons in the orbiting shell between the resistive cylinders n_e is the total number of electrons contained. As is characteristic of resistive instabilities, the larger the resistance or the number of electrons the greater the instability growth rate.

9

Experimentally, we find that the device emits microwaves only if a high-Q cavity resonator is placed around the wire (see Fig. 1), and if the discharge current is raised above a critical threshold. One of our early resonators that worked quite well was a beer can with holes drilled to extract beer and the tab left intact. Applying about 2000 V in a square wave pulse results in the following behavior. First, the discharge current gradually builds up over about 50 microseconds. This time decreases with increasing gas pressure and quantitatively is consistent with the buildup of an ionizing electron cloud by a rotatng electron avalanche.

Next, a chain of intense microwave pulses is emitted. The radiation, Fig. 3, can escape via the central wire, and the radiation intensity and polarization pattern is consistent with the wire acting as a simple antenna. Radiation can also be removed through an aperture in the cavity. A typical measured peak power output for emission at 3 cm wavelength is several watts, or 100 times that of our test klystron.

We have checked the dependence of the emitted frequency on wire size and applied voltage, and have obtained reasonable agreement with Eq. 1. By using diode detectors, and waveguides as high pass filters, we obtain
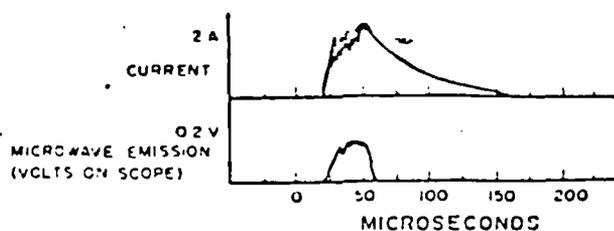

Fig. 3. Operation during voltage pulse. The current dies out on this graph because the supply was a small charged capacitor.

the increase in frequency with applied voltage as shown in Fig. 4. Data were taken at 3 cm, 8 mm, 5.5 mm, and 4 mm (the last not shown). We note that the filters are high pass only, so that we do not know if the lower frequency emissions persist as the voltage is increased. At present, the only restriction on working at still shorter wavelengths is the lack of diagnostic apparatus. In any case, the observation of the predicted dependence between frequency and voltage supports the validity of our model.
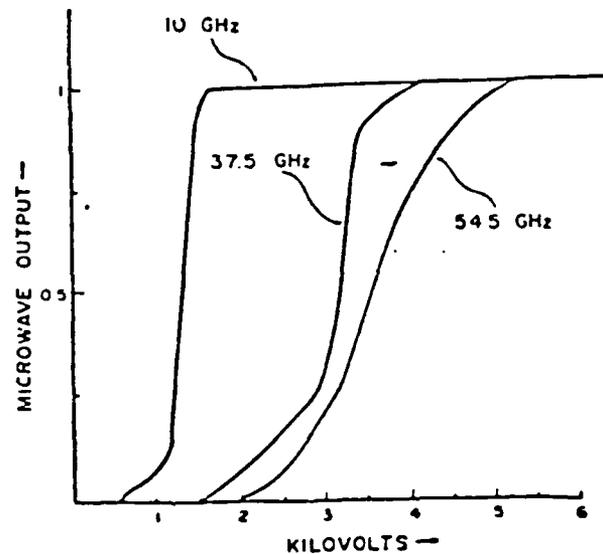

Fig. 4. Graph of normalized microwave detector output discharge voltage, showing frequency dependence on voltage.

Although our system contains many small electron orbits of differing frequency, we feel that we can produce narrow-band emission by proper choice of the cavity resonator. An analogous system would be a

11

turneable dye laser, in which the dye can emit over a broad range, $(\Delta\lambda/\lambda) \approx$ 0.1, but the emission is forced into the desired range by the external cavity. We have tried using an etalon of stacked glass plates as one side of a rectangular cavity to force the radiation into $\lambda = 8$ mm, with apparent success. Another possibility would be to use a tilted diffraction grating as one side of a rectangular cavity and to tune the device by changing the angle of tilt. Still another would be to fill the cavity with a resonant molecular gas. Finally, one approach we did use successfully was to make a sufficiently narrow cavity that $\lambda = 3$ cm did not fit inside (was beyond cutoff) and hence was not emitted.

A new concept we are testing is making a cavity of <u>antimesh</u> - metal plates on an insulating substrate. Waves short compared to the plate size reflect and are contained in the cavity. These produce stimulated emission. Waves long compred to the plate size see an insulating layer and freely escape from the cavity. These cannot produce stimulated emission, and die out. The concept will be developed later.

IV. History of the Orbitron

The basic maser project started about 6 years ago, when Igor Alexeff, the principal investigator of this proposal, decided that classical masers were the way in which to proceed to produce sub-millimeter radiations because large, multi-mode cavities gave lots of available room inside and lots of surface area for cooling.

Prof. Alexeff's first graduate student in this area, Larry Barnett, constructed an electron cyclotron maser using resonance in a magnetic field to determine the frequency. A radial electric field was used to break the degeneracy condition for orbits.[2] If the orbit frequency does not vary with orbit energy, phase bunching and hence coherent emission is not possible. Other electron cyclotron masers, such as the Russian gyrotron, have been constructed successfully, but their disadvantage is that they require relativistic electrons. They used the relativistic mass increase with energy to break the degeneracy condition.

The major problem with Larry Barnett's project was that the mathematics were cumbersome. Prof. Alexeff attempted to simplify the mathematics, and reduced it to two pages of computation on a flight from Los Angeles to Santa Barbara.

The mathematics was applicable to any problem with cylindrical geometry. It was essentially the beam - plasma interaction bent into a circle. He asked his former graduate student, Dr. Osamu Ishihara, to check

---

[2]L. R. Barnett and I. Alexeff, in Proceedings of the IEEE International Electron Devices Meeting, Washington, D.C. 1979 (Institute of Electrical and Electronics Engineers, New York, 1979), Technical Digest No. CH-1504-0/79/000-0/068.

13

the mathematics. After some correspondence, they decided that the mathematics was satisfactory.

Prof. Alexeff had been experimenting with a plasma system in which electrons are confined in orbits around a positively charged wire. The system is both an interesting plasma in itself, and it forms the basis of a high voltage opening switch.[3]

Successful microwave emission was first observed at 3 cm in June, 1979 by Fred Dyer, who was helping at the time. We were attempting to operate in the switch mode, and were using a capacitor bank to provide both high voltage and high current. The cathode surrounding the wire was the microwave cavity. The pulsing of the current to high values brought the device over the maser threshold. As with all masers and lasers, there is a discrete threshold in power input, below which nothing happens. Fred Dyer had anticipated the emission of microwaves, and had installed a 3 cm microwave detector on the switch.

Once the maser operation succeeded, the power level was quite high. We were able to pick up 3 cm radiation 15 feet away across the room, using only a microwave horn and diode. The radiation initially escaped from the cavity along the central positive wire, which then acted as an antenna. This mode was confirmed by studying the radiation pattern and polarization direction. Subsequently, we have extracted the microwaves from an aperture in the cavity wall. We discovered that an aluminum beer can made an excellent microwave cavity, since aluminum has almost as high a conductivity as copper.

[3]Igor Alexeff and Fred Dyer, IEEE Transactions on Plasma Science, Vol. PS-8, No. 3, Sept. 1980. (In published References Sections of this Report).

14

Extension of our results to shorter wavelengths were frustrated by our univeristy having no equipment for wavelengths shorter than 3 cm. Fortunately, we were able to borrow microwave diodes for 8 mm, 5.5 mm, and 4. mm, and bolometers for 2 mm, from Oak Ridge National Laboratory due to the assistance of Owen Eldridge, Alan England, Marshall Loring, and John Wilgen. We quickly established that radiation could be produced down to 4 mm (the last production being erratic), and that the peak frequency dependence on wire diameter and voltage fitted rather well. Radiation at 2 mm on the bolometer was never clearly observed, and we suspected that the device requires too much integrated power to be useful. Subsequently, we returned the ORNL equipment, and borrowed NASA equipment for wavelengths to 4 mm from Professor J. Reece Roth at the University of Tennessee, Knoxville. This equipment was furnished by UTK by NASA as part of a contract with ONR, in April, 1980.

Several most interesting experiments were done with the apparatus. Stimulated emission from a 3 cm klystron source wa observed. Observations at several frequencies simultaneously showed the time dependence of the radiation, with 3 cm emission first, then 8 mm, and finally 4 mm. This is consistent with the presence of an orbiting electron cloud that collapses on the wire as energy is removed. If the maser action is interrupted by destroying the cavity Q, the wire gets hot from the discharge. Otherwise, most of the energy apparently goes into radiation. The time delay between applying voltage and observing maser action is

15

consistent with the formation of an electron avalanche around the wire. The time grows shorter with increasing gas pressure.

Additional interesting observations are that intense pluses of microwaves travel over the surfaces of our hollow waveguides to the detectors. They may be interrupted by aluminum foil collars. Additionally, at 8 and 4 mm, the microwaves are emitted parallel to the central wire in a collimated beam!

We found that a weak magnetic field reduced the emission of microwaves. We then screened out the earth's magnetic field with a metal shield, and found that the current threshold for microwave emission was reduced by a factor of ten. In addition, pulsed power operation was no longer required, the device producing a continuous train of pulses when supplied by DC.

By using a Fabry - Perot resonator of stacked plates of glass, we were able to concentrate the radiation in the 8 mm band. This was verified by using a tuneable stub on the 8 mm diode, and observing the peaked response as the stub was tuned.

Power can, in theory, be increased by using multiple wires. The electron clouds orbiting each wire should phase-lock, and for pulsed power, the power output should go as the number of wires squared. Preliminary studies using multiple wires seemed to support this observation. In addition, stimulated emission was observed by operating a maser below the threshold level and irradiating it as $\lambda = 3$ cm. If an electron cloud phase-

locks with an external oscillator, it should phase-lock with the rf field of another electron cloud!

We have made two very important improvements in the design and construction of the maser itself. First, we have discontinued using the small holes in the cathode surrounding the anode wire for our electrostatic mirrors. These holes are hard to align with the wire, are short-circuited by plasma discharges, and don't confine electrons close to the surface of the wire as there is no parallel E-field at the surface of the wire. Instead, we place the electrostatic mirrors on the anode wire itself by etching steps in the wire using an electrochemical technique developed by Muller for field-emission microscopes.[4] Thus, the problems described above are all overcome. Using the electrostatic mirror-on-wire technique with an open-ended cavity results in completely reliable microwave emission at $\lambda = 2$ mm.

Our second improvement eliminates a serious problem in our maser-phase mixing and Landau damping due to electron motion parallel to the wire. We note that the electrons moving parallel to the wire can absorb energy from waves moving parallel to the wire. Also, if the wire is slightly misaligned with the radiation field inside the cavity, an electron emitting at one end of the cavity can be absorbing at the other end. This effect of alignment can be very serious when sub-millimeter operation is considered, as sag in the wire of $\lambda/2$ can cause the above effect. Both effects can be eliminated if electrons are prevented from moving parallel to the wire. This is accomplished by etching a chain of steps - multiple

[4]Field-Ion Microscopy, Erwin W. Muller and Tien Tzou Tsong, P. 119 (Elsevier, New York, 1969).

electrostatic mirrors-down the length of the wire. A test at $\lambda = 3$ cm with a wire with two mirrors and 3 steps produced much higher power levels than observed before. The microwave pulses in the diode detector now flat - topped due to diode breakdown.

V. UTK Plasma Laboratory and Staffing

The work on this maser will be conducted at the UTK Plasma Laboratory in Room 101 Ferris Hall. This laboratory comprises on air-conditioned ground floor room of 1800 sq. ft. floor space, with a high-stress floor and loading dock.

The principal staffing members are Professor Igor Alexeff and Mr. Frederick Dyer. Professor J. Reece Roth is a consultant, he already has an AFOSR contract. A description of the skills of these investigators are as follows:

Francis Frederick Dyer

Fred Dyer was a former student at the University of Tennessee who began working with Igor Alexeff in developing several inventions. These include an improved plasma light source, a high-voltage opening switch, and the free-electron maser. His speciality is in building apparatus and getting it to operate.

Prof. Igor Alexeff

Prof. Igor Alexeff, the principal investigator, has been at the univesity since 1971. He maintains an active consulting practice both nationally and internationally, conducts an active on campus program of

experimental plasma research, and teaches a variety of up-to-date plasma related courses on the graduate and undergraduate levels. Of these, probably the most unique is a junior level introductory course in plasma and electro-optics. Included in this course is a laboratory that allows students hands on experience with Langmuir probes and other practical plasma applications. In the past five years, his consulting activities have included regular interactions with the Isotope Separation Evalution Group at K-25, Union Carbide, at Oak Ridge, in which he has made significant classified contributions to the plasma isotope separation program; consultations with the C.S.G. Inc. of Sucre, Bolivia, in which he has participated in the development of a more efficient electric motor based on the nonlinear properties of saturable iron; consultations with Motor Magnetics, Inc. of New York, N.Y., on a new principle of electric motor design, consultations with the Ultra-Resonance Corp. of Los Angeles, on the subject of plasma isotope separation, and the Energy Resource Group, of Arlington, Virginia on the subject of high beta tokamak research. He has been in great demand as an academic as well as an industrial consultant to help establish and collaborate with plasma research programs in other countries. Thes eposts have included: Summer 1973; Visiting Professor, Physics Department, Universidade Federal Fluminense, Niteroi, Rio de Janeiro, Brazil where he helped set up a fusion research program; Summer 1976; Visiting Professor, Department of Physics, University of Natal, South Africa; Summer 1975; Visiting Professor Physical Research Laboratory, Ahmedabad, India, where he helped set up a plasma research effort. A

result of this was a joint U.S. - India cooperative agreement funded by the NSF in the U.S. , of which Dr. Alexeff is a principal investigator at this time. Spring 1973; Visiting Professor, Institute of Plasma Physics, Nagoya, Japan, where he collaborated on several research papers on plasma waves. Dr. Alexeff's research activities at the University of Tennessee have resulted in a steady output of results on topics such as more efficient plasma lighting devices; submillimeter microwave power generation; joint discovery (with J. R. Roth of the geometric mean plasma emission, a new mode of electro-magnetic emission from plasmas which may be useful in communications; plasma-based isotope separators, plasma diagnostics, and fusion research.

From 1960 to 1971, Dr. Alexeff was Group Leader, Controlled Thermonuclear Division, Oak Ridge National Laboratory. At one point in his career at ORNL, Dr. Alexeff directed three groups dcing basic plasma research, turbulent heating, and levitated toroidal multipole experiments. While at ORNL, Dr. Alexeff made fundamental contributions to the theory and experimental investigation of ion-acoustic waves (which can affect the performance of plasma diodes, mercury-vapor rectifiers, and isotope separation devices), and to development of the "Burnout" experiment, wich was an early steady-state electric field dominated plasma which heated ions to kinetic temperatures higher than any previously observed in the main-line fusion program of this country. He was awarded the Weinberg prize ($2800) by the past director of ORNL for his efforts.

Prof. J. Reece Roth

Prof. J. Reece Roth joined the UTK staff in 1978, having previously been director of the NASA-Lewis Bumpy Torus Project. While at the NASA Lewis Research Center, Dr. Roth made at least two pioneering contributions to fusion-related superconducting magnet technology. He was responsible for the basic design and distinctive features of the "Pilot Rig" superconducting magnet facilty at NASA Lewis in Cleveland. This facility went into service in December, 1964, and was the first such facility ever to be used for plasma physics or controlled fusion research. Dr. Roth's second contribution in the magnet area was as the engineer responsible for the basic design and distinctive features of the NASA Lewis superconducting bumpy torus magnet facility. This facility went into service in 1972, and was the first superconducting magnet facility anywhere in the world to generate a toroidal magnetic field. It is still the only such facility in this country.

In studying the plasmas which these facilities were designed to confine, Dr. Roth has discovered two previously unrecognized modes of plasma instability. The first of these is the "continuity-equation oscillation" (the name is Dr. Roth's own) which was observed in the Pilot Rig in 1967. Dr. Roth was the first to investigate this oscillation experimentally, and the first to describe it theoretically. His work on the continuity-equation oscillation has been recognized in standard monographs and compilations such as A. I. Akhiezer et al. Plasma Electrodynamics, and F. Cap's Handbook on Plasma Instabilities, Vol. 1.

Dr. Roth was also the first to report the experimental observation of the "Geometric Mean Plasma Emission" (Dr. Roth also named this instability). His data was explained theoretically by Prof. lgor Alexeff, and they jointly reported the discovery of this new instability in August, 1979.

Dr. Roth has authoritative knowledge of Penning discharges, the use of superconducting magnet facili:'es in plasma and fusion application; the continuity-equation oscillation and moving striations; and ion heating and transport in a modified Penning discharge. Dr. Roth was the first to identify the physical mechanism responsible for ion heating in a modified Penning discharge, and the first to describe it.

Dr. Roth's academic responsibilities include teaching a required undergraduate course on plasma engineering from his own notes, and a three-term graduate sequence on fusion, also from his own notes.

APPENDIX A

STAFF RESUMES

I. Alexeff

F. Dyer

J. R. Roth

APPENDIX A

BIOGRAPHICAL SKETCH

Igor Alexeff

1. Name and Date of Birth:

   Igor Alexeff
   January 5, 1931

2. Academic Rank:

   Professor of Electrical Engineering

3. Degrees, With Field, Institution and Date:

   Professional Engineer, Registered 1978, State of Tennessee.
   University of Wisconsin, Ph.D - 1959.
   Harvard University, Cambridge, Mass., Bachelors Degree - 1952.

4. Number of Years Service on this Faculty: 13

   Original Appointment - September, 1971

5. Other Related Experience - Teaching and Industrial:

   Westinghouse Research Lab. - Nuclear Physics Research, 1952-53

   University of Zurich, Switzerland-Nuclear Physics Research, 1959-60.

   ORNL Thermonuclear Division Plasma Physics Research, 1960-July 31, 1971.

   University of Tennessee, 1971-Present

   Visiting Professor:

   1973 Institute of Plasma Physics, Nagoya, Japan

   1975 Physical Research Laboratory, Ahmedabad, India

   1976 University of Natal, South Africa

   1978 Universidade Federal Fluminense, Rio de Janeiro, Brazil

6. Consulting:

   Oak Ridge National Laboratories, Motor Magnetics, Hughes Research Labs

7. States in Which Registered: Tennessee

8. Principal Publications of Last Five Years:

   I. Alexeff, G. Procobelli and A. Hirose, "Refraction of Ion Accoustic Waves in Thermal and Density Gradients," Physics Letters, 57A(5): 453-54, 1977.

I. Alexeff and Bimla Buti, "Trip Report," IEEE Transactions of Plasma Science, PS-5(2): 131-133, 1977.

I. Alexeff, "Critique on Isotope Separators,: Journal of Applied Physics, 1978.

I. Alexeff, "Chance Look and Striking Photograph (Occulation of Venus by Morning).", The Oak Ridger, 26 December, 1978, Page 1.

I. Alexeff, "Instability of limit on Throughout for Calutrons," IEEE Transaction on Plasma Science, 1978.

I. Alexeff and Osamu Ishihara, "Landau Damping for students," IEEE Transactions on Plasma Science, PS-6(2): 212-219, 1978.

I. Alexeff, O. Ishihara, H. J. Doucet, and W. D. Jones, "Reflection and Absorption of Ion-Acoustic Waves in a Density Gradient,: Physics of Fluids, 1978.

I. Alexeff and J. R. Roth, "Dispersive Properties of the Geometric Mean Plasma Emission," APS Bulletin 24(8): 1090, 1979.

I. Alexeff and F. Dyer, "Increasing the Efficiency of Light Emission from a Plasma by Electrostatic Confinement," Transaction on Plasma Science, December, 1979.

I. Alexeff, C. L. Rao and Fred Dyer, "Experimental Observations of Ion-Acoustic Wave Reflection," Proceedings, 21st Annual Meeting, Division of Plasma Physics, 1979.

I. Alexeff, J. R. Roth, and R. Mallavarpu, "Experimental Observation and Theoretical Description of New Plasma Emission at the Geometrical Mean Plasma Frequency," IEEE International Conference on Plasma Science, pp. 155-156, 1979.

I. Alexeff, J. R. Roth, and R. Mallavarpu, "Electric Field Penetration and Anomalous Resistivity in an Electric Field Dominated Toroidal Plasma," APS Bulletin, 24(8): 1056, 1979.

I. Alexeff, J. R. Roth and R. Mallavarpu, "New Mechanism for Electromagnetic Emission Near the Geometric Mean Plasma Frequency," Physical Review Letters, 43(6): 445-449, 1979.

I. Alexeff and F. Dyer, "Microwave Emission from a Maser by Use of Plasma-Produced Electrons Orbiting a Positively Charged Wire," Physical Review Letters, 45(5): 351-354, 1980.

I. Alexeff and F. Dyer, "A Simple High-Voltage Opening Switch Using Spoiled Electrostatic Confinement," IEEE Transactions on Plasma Science, Vol. PS-8(3), page 163, 1980.

I. Alexeff, J. R. Roth, J. D. Birdwell, and R. Mallavarpu, "A New Mechanism for Electromagnetic Emission and Anomalous Resistivity from Equal and Oppositely Directed Beams Interacting with Heavy Ions,: IEEE International Conference on Plasma Science, Madison, Wisconsin, 1980.

I. Alexeff, J. R. Roth, J. D. Birdwell and R. Mallavarpu, "Electromagnetic Emission and Anomalous Resistivity from Equal and Oppositely Directed Electron Beams." The Physics of Fluids 24, 1348 (1981).

L. Alexeff, "Instability Threshold for a Calutron (Isotype Separator) with Only One Istotype Species, IEEE Transactions on Plasma Science Vol. PS-11, 90 (June 1983).

L. Alexeff and Fred Dyer, "The Orbitron Maser," F 2.2, 1983 International Conference on Infrared and Millimeter Waves, Dec. 83, Miami Beach, Fla. CH 1917-4/83/0000 - 0F24 $0.75 c 1983 IEEE.

L. Alexeff and Fred Dyer, "The Orbitron Maser" p. 394 proceedings 1984 International Conference on Plasma Physics, June 27 - July 3, 1984, Lausanne, Switzerland.

I. Alexeff - "Note on the Shroud of Turn," Biblical Archaeology Review, p. 25, July/Aug. 1984.

9.   Scientific and Professional Societies of which a Member:

American Physical Society

Sigma Xi

IEEE

University Fusion Association

10.   Honors and Awards:

Secretary, Treasurer, Vice President, President, Oak Ridge section of the IEEE

Fellow IEEE

Fellow American Physical Society

Secretary-Treasurer American Physical Society Plasma Physics Division '83-84

Member - Steering Committee of University Fusion Association ('82-'83-'84)

Listed in Who's Who in America

Listed in Who's Who in the World

Listed in Who's Who in South and Southeast

Guest, Russian Academy of Science - paid two visits

Chairman - IEEE Plasma Society, '83, '84

Secretary, IEEE Plasma Society (1982, '81, '80)

Member, MENSA

Vice President, IEEE Nuclear and Plasma Sciences Society 1983

Vice President, Southern Appalachian Science Fair '82-'83, President, '84-'85

Chairman 1974 Gorden Conference on Plasma Physics

Organizer 1976 School of Plasma Physics Ahmedabad, India (with USNSF support - co-chaired with Dr. Bimla Buti)

Organizer, 1st IEEE International Conference on Plasma Science Knoxville (1974)

Member, IEEE Fellow Committee '83-'84'-'85

University of Tennessee Chancellor's Research Scholar, 1984.

IEEE Centinnial Medal Awarded 1984.

President, Tennessee Inventors Association, 1984.

11. List any specific programs in which faculty member has participated to improve teaching and professional competence:

Speaker - WATTec
Sponsored research activities
Speaker - IEEE Knoxville Section
Speaker - IEEE Oak Ridge Section

12. Languages-German, Russian, Basic

13. <u>Recent Contracts</u>

Sponsor
AFOSR
Project
"Millimeter Microwave Emission by use of Plasma Produced Electrons Orbiting a Positively - Charged Wire."
Funding:
$78,000 November 15, 1983 - November 15, 1984

Sponsor
NSF
Project
"Engineering Aspects of Plasma Waves"
Funding
$37,530 December 15, 1982 - December 15, 1983

14. Ph.D. 2 Students

Phil Ryan (ORNL)
Wlodzimierz Nakonieczny (Physics)

15. Recent invited papers

1. "Millimeter Microwave Production from a Maser by use of Electrons Orbiting
Positively-Charged Wire (Synthetic Atoms).
Igor Alexeff, Division of Plasma Physics Twenty-Third Annual Meeting,
American Physical Society, New York, NY (12-16 October 1981).

2. "Elementary Plasma Demonstrations Under $10.00 Each"
Igor Alexeff.
San Francisco Meeting of the American Physical Society, 25-28 January,
1982.

16. Patents in Force (3) - High Voltage Opening Switch, Microwave Masers

17. Technical Record:

At present, I am a full professor of Electrical Engineering at the University
of Tennessee, Knoxville, and am a registered professional engineer in the state
of Tennessee. I have several industrial consulting contracts. My present
university research is sponsored from these contracts, the University, The U.S.
National Science Foundation, and the U.S. Air Force. The work concerns plasma
engineering, plasma isotope separation, electromagnetics, and optics.

In earlier times, I spent 10 years (1960-1971) at the Oak Ridge National
Laboratory in fusion research. During this period I was at one time group leader
of 3 groups at once, was responsible for a budget of over $500,000/year, and
authored 50 refereed papers.

I spent one year at Westinghouse (1952-1953), where I developed a neutron
energy spectrometer that contributed to nuclear submarine engine development.

I have about 100 refereed published papers in the fields of Plasma Physics,
Plasma Engineering, Nuclear Physics, and Education in the above fields. My
major discoveries were in the fields of plasma waves, plasma turbulence, and
plasma heating.

Igor Alexeff
Page 6

       Finally, I have been able to help some very fine undergraduate and graduate students start their careers. This is probably my most important contribution to society.

18.   <u>Publications:</u>

1948
Electronic Relay, Radio Craft, March 1948, p. 40.

1955
The Scattering of 4.4 Mev Neutrons by Iron and Carbon, (with B. Jenkins, J. Weddell, and R. L. Hellens) Phys. Rev. 98, (1955).

1955
Evapor-Ion Pump Performance with Noble Gases (with E. C. Peterson) Vacuum Sump. Trans. p. 87, 1955.

1955
Evapor-Ion Pump Development, (with M. F. Bina and R. M. Sanders), Phys. Rev. 98, 251A (1955).

1955
Evapor-Ion Pump Performance with Noble Gases, (with E. C. Peterson), Phys. Rev. 100, 123A (1955).

1957
An Easily Remembered Derivation of PVR-C for the Student, AM.J. Phys. 25, 488 (1957).

1959
Polarization in Proton-Proton Scattering at 3.5 Mev, (with R. I. Brown, R. A. Lux, S. J. Moss, and W. Haeberli), Bull. AM. Phys. Soc. 4. 253 (1959).

1960
Attempts of Produce H 25 by Charge Exchange, Proc. Inter. Symp. Polarization Phenomens of Nucleons, Basel, p. 134 July, 1960.

1960
Polarization in Proton-Proton Scattering Near 3.3 Mev. (with W. Haeberli) Nuclear Physics 15, 609 (1960).

1961
A Vacuum Manometer Using Ultra-Violet Light, Second Inter. Congress Inter. Organization for Vaccum Sci. Technol. Oct. 1961.

1961
Observation of Ionic Sound Waves in Gaseious Discharge Tubes. (with R. V. Neidigh) Proc. Fifth Inter. Conf. Ionization Phenomena P. 1523, 1961.

1962
A Way to Measure Plasma Density-The Plasma Sweeper (with R. V. Neidigh) Proc. 3rd Symp., Eng. Aspects of Magnetohydrodynamics, Mar. 1962.

1962
Experiments concerning The Magnetic Confinement of a Cold Plasma (with R. V. Neidigh and C. D. Shipley) J. Nucl. Energy. Part C, 4, 263 (1962).

1962
Experimental Observation of Plasma Electron Pressure (with R. V. Neidigh) Phys. Rev. 127, 1. (1962).

1962
A Vacuum Namometer Using Ultraviolet Light, pp. 472-75 in Trans. 8th Vacuum Symposium and 2nd International Congr. Vacuum Technology. Ed. L. E. Preuss, Macmillan, New York, 1962. (Work Done at the Physical Institute, University of Zurich, Switzerland, and Supported by the U. S. National Science Foundation. Patent Assigned to the high voltage Engineering Corp., Burlington.

1962
A Device to Measure the Rate of Flow of a Plasma, The Plasma Eater, (with R. V. Neidigh), Bull. AM. Phys. Soc. 7, (4), (1962).

1962
Random Injection into a Mirror Geometry, (with R. V. Neidigh and E. D. Shipley), Bull. Am. Phys. Soc. 7, (6), (1962). A-M3.

1962
Ionic Sound Waves in an Electromagnetic Isotope Separator, (with A. M. Veach and O. C. Yonts), AM. Phys. Soc. 7, (1962).

1963
Direct Measurement of Ionic Sound Wave Velocity (with W. D. Jones) Intern. Ionization Phemomena Gases, proc. 6th, Paris, July, 1963.

1963
Observations of Ionic Sound Waves in Plasmas-Their Properties and Applications, (with R. V. Neidigh) Phys. Rev. 129, 516 (1963).

1963
Optimum Energy For Plasma Confinement (with R. V. Neidigh and E. D. Shipley) Phys. Fluids 6, (1963).

1963
A Plasma Flowmeter. The Plasma Eater (with R. V. Neidigh) Nucl. Fusion 3, 23 (1963).

1963
Proceedings Sixth International Conference on Ionization Phenomena in Gases, Paris 1963. (To be Published).

1963
A Way to Measure Plasma Denisty-The Plasma Sweeper, (with R. V. Neidigh), pp. 141-52, Eng. Aspects of Magnetohydrodynamics, 3rd., Symp., Gordon and Breach, 1963.

1963
Plasma Denisty Measurement by Casting a Shadow in Evaporated Gold. (with R. V. Neidigh and W. F. Peed), Bull. Am. Phys. Soc. 8, (1963). F4.

1963
Hot Electron Plasma By Beam-Plasma Interaction, (with R. V. Neidigh, W. F. Peed and E. D. Shipley). Phys. Rev. Letters 10, 273, (1963).

1964
Beam-Plasma Interaction Experiments and Diagnostics (with R. V. Neidigh and W. F. Peed) Phys. Rev. 136, (1964).

1964
Experiments with Ioffee Magnetic Fields, (with R. V. Neidigh), Bull. Am. Phys. Soc. 9, 327 (1964).

1964
The Velocity of Moving Striations in Discharge Tubes as a Function of Gas Pressure, (with W. D. Jones), Bull, AM. Phys. Soc. 9, 469 (1964).

1964
Some Effects of a Magnetic Field on Coulobm Scattering, (with R. V. Neidigh and D. Montgomery). Bull. Am. Phys. Soc. 9, 325 (1964).

1964
Observations of Discharge-Tube Striations Using an Image Converter, (with W. D. Jones and R. V. Niedigh), Bull. Am. Phys. Soc. 9, 323 (1964).

1964
A Possible Source of the Energetic Ions emitted From the Pressure Gradient Arc, (with R. V. Neidigh), Bull. Am. Phys. Soc. 9, 469 (1964).

1964
Observation of Burnout in a Steady-state Plasma, (with R. V. Neidigh), Phys. Rev. Letters 13, 179 (1964).

1965
Stroboscopic Shutter for Visulaay Studying Plasma Oscillations, (with W. D. Jones, and R. V. Neidigh), Rev. Sci. Instr. 36, 44-47, 1965.

1965
Sampling Oscilloscope as a Coherent Wide-Band Detector, (with P. Bletzinger, A. Garscadden and W. D. Jones) J. Sci. Inst. 42, (1965).

1965
Some Stabilized Plasma Experiments, (with R. V. Neidigh), Phys. Fluids 8, (1965).

1965
Collisionless Ion-Wave Propagation and Determination of the Compression Coefficient of Plasma Electrons. (with W. D. Jones). Phys. Rev. Letters 15, 286-88. (1965).

1965
Study of Ionic Sound Wave Pulses Using Electronic Noise Rejection. (with W. D. Jones). Bull. Am. Phys. Soc. 10, 200 (1965). (Presented by Alexeff at Culham Laboratory Study Group on Plasma Waves, Sept. 21-25, 1964— No Formal Paper Prepared).

1965
Burnout By Beam-Plasma Interaction, (with R. V. Neidigh and W. F. Peed), Bull., Am. Phys. Soc. 10, 523 (1965).

1965
Properties of Ionic Sound Waves in a Collisionless Discharge-Tube Plasma, (with W. D. Jones,) Bull, Am. Phys. Soc. 10, 509 (1965).

1965
Observation of Cutoff of Ionic-Sound-Wave Propagation Near the Ion-Plasma Frequency, (with W. D. Jones), Bull, Am. Phys. Soc. 10, 509 (1965).

1966
Plasma-Density Measurement in a Hollow-Cathode Arc by Arc Reversal, (with W. Halchin, W. D. Jones and J. F. Potts), ORNL-4010, Sept. 1966.

1966
Beograd, Yugoslavia, Aug. 1965 (ED. By B. Perovic and Tosic), Gradevinska Knjiga, Beogra Yugoslavia, 1966.

1966
A Simple Thermal Instability in Discharge Tubes—A Possible Cause of Moving Striations, Bull. Am. Phys. Soc. II, 551 (1966).

1966
Plasma Heating and Burnout in Beam-Plasma Interaction, (with W. D. Jones, R. V. Neidigh, W. F. Peed and W. L. Stirling), Proc. 2nd Conf. Plasma Physics and Controlled Nuclear Fusion Research, Culham, England, Sept. 6-10, 1965, IAEA, Vienna. 1966 Vol. II, P. 781. Sti/Pub/111. (Cn-21/102).

1966
Neutron Source Strengths in Burnout V, (with R. V. Neidigh and W. F. Peed), Bull, Am. Phys. Soc. II. 575 (1966).

1966
Iron-Core Minimum B Magnet, (with W. Halchin), pp. 106-09 Proc. Engineering Problems of Controlled Thermonuclear Research Symp., Gatlinburg, Tenn., Oct. 1966, Conf-661016.

1966
Electron Emitting and Electron-Collecting Probes as Ion Wave Detectors, (with W. D. Jones), Phys. Letters 20, 269-71 (1966).

1966
Development of a Hot-Electron Plasma Blanket, (with W. L. Stirling, R. V. Neidigh + V. J. Meece), J. Nucl. energy. Pt. C. 8, 157-58 (1966).

1966
Iron-Core Electromagnet Producing a Magnetic Well with Nonzero Minimum Fro Plasma Confinement. J. Appl. Phys. 37, 2166).

1966
Plasma Decay Technique to Measure Density in Discharge Tubes, (with W. D. Jones and J. Lohr), Phys. Fluids 9. 1403-06 (1966).

1966
Varying Plasma Electron Temperature in Discharge Tubes by a Simple Auxiliary Electrode. (with W. D. Jones), Appl. Phys. Letters 9, 77-79 (1966).

1966
Observations on the Velocity of Moving Striations. (with W. D. Jones), Phys. Fluids 9. 1871-72 (1966).

1966
Alternative Method for Exciting Electron Plasma Oscillations with Transverse Electromagnetic Waves, (with D. Montgomery), Phys. Fluids 9, 2076-77 (1966).

1966
Plasma Heating and Burnout in Beam-Plasma Interaction, (with W. D. Jones, R. V. Neidigh, W. F. Peed and W. L. Stirling), Vol. 2, pp. 781-99, Plasma Physics and Controlled Nuclear Fusion Research, Proc. 2nd Conf., Culham, England, Sept. 1965 Intern. at Energy Agency, Vienna, 1966.

1966
Parametric Excitation of Transverse Waves in a Plasma, (with D. Montgomery), Phys. Fluids 9, 1362-66 (1966).

1966
A Study of the Properties of Ionic Sound Waves, (with W. D. Jones), pp. 330-35, Phenomena in Ionized Gases, Proc. 7th Intern. Conf., Beograd, Yugoslavia, 1966.

1966
Simple Momentum Probe for Plasma Studies, (with W. D. Jones, D. Montgomery and M. Rankin). pp. 62-66, Phenomena in Ionized Gases, Proc. 7th Intern. Conf.

1967
Electron Temperature Variation Induced Effects and Landau Damping of Ion Acoustic Waves, (with W. D. Jones and D. Montgomery), ORNL, April 1967.

1967
Production of D-D Reactions by Beam-Plasma Interaction in the Steady State, (with W. D. Jones and R. V. Neidigh), Phys. Rev. Letters 18, 1109-12 1967.

1967
Electron-Temperature Variation Induced Effects and Landau Damping of Ion Acoustic Waves, (with W. D. Jones, and D. Montgomery), pp. 371-95, Physics of Quiescent Plasmas, Proc. Conf., Frascati, Italy, Jan. 1967, Laboratori Gas Ionizzati, Associazione Euratom-Cnen, 1967.

1967
Observation of the Ion-Temperature Contribution to the Ion-Acoustic Wave Velocity, (with W. D. Jones, and M. G. Payne), Bull, Am. Phys. Soc. 12, 770 (1967).

1967
Energetic Particle Scattering by Laboratory Plasmas, (with D. Montgomery and C. Roque), Bull. Am. Phys. Soc. 12, 749 (1967).

1967
Demonstration of Landau Damping of Ion-Acoustic Waves in Discharge-Tube Plasmas, (with W. D. Jones and D. Montgomery), Bull. Am. Phys. Soc. 12, 770 (1967).

1967
Controlled Landau Damping of Ion-Acoustic Waves, (with W. D. Jones), Bull, Am. Phys. Soc. 12, 711-12 (1967).

1967
Landau Damping of Ion-Acoustic Waves Produced by a Ligh Contaminant. (with W. D. Jones and D. Montgomery), p. 357, Phemomena in Ionized Gases, 8th Intern. Conf., Vienna, Austria, Sept. 1967, Inter, At. Energy Agency, Vienna, Austria, 1967.

1967
Dispersion of Ion-Acoustic Waves, (with K. Lonngren, D. Montgomery and
W. D. Jones), Phys. Letters 25A, 629-30 (1967)

1968
Oscillations Present in Plasma-Electron Heating by an Electron Beam,
(with G. E. Guest, D. Montgomery, R. V. Neidigh and D. J. Rose), Phys.
Rev. Letters 21, 344-47 (1968).

1968
Azimuthally Localized Fluctuations in a Levitated Toroidal Quadrupole,
(with M. Roberts and W. Halchin), Phys. Letters 26A, 590-91 (1968).

1968
Excitation of Pseudowaves in a Plasma Via a Grid, (with W. D. Jones and K.
Lonngren), Phys. Rev. Letters 21, 878-81 (1968).

1969
Experimental Stron Turbulent Heating, (with R. V. Neidigh, G. E. Guest,
W. D. Jones, D. C. Montogomery, D. J. Rose and W. L. Stirling). Book.
Proc. Plasma Physics and Controlled Nuclear Fusion Research, 3rd, IAEA
Conf., Novosibirsk, USSR, Aug. 1968, IAEA, Vienna, Austria, Vol. 2, 693-
708, 1969.

1969
ORNL Leviatated Toroidal Multipole Program, (with M. Roberts, R. A.
Dory, W. Halchin and W. L. Stirling). Book. Proc. Plasma Physics and
Controlled Nuclear Fusion Research, 3rd IAEA Conf., Novosibirsk, USSR,
Aug. 1968, IAEA, Vienna, Austria, Vol. 2, pp. 651-665, 1969.

1970
I. Alexeff, W. D. Jones and M. Widner, "Multiple Pseudowaves Produced by
a Single Voltage Pulse, " The Physics of Fluids, Vol. 13, No. 6, pp. 1519-1524,
June, 1970.

1970
W. L. Stirling, M. Roberts, and I. Alexeff, "Effects of Introducing Supports
in a Levitated Toroidal Quadrupole," The Physics of Fluids, Vol. 13, No. 7,
pp. 1888-1889, July, 1970.

1970
I. Alexeff, K. Estabrook, A. Hirose, W. D. Jones, R. V. Neidigh, J. N. Olsen,
F. R. Scott, W. L. Stirling, M. M. Widner, and W. R. Wing. "Understanding
Turbulent Ion Heating in the (ak Ridge Mirror Machine, "Burnout V"
Physical Review Letters, Vol. 25, No. 13, pp. 848-851, September, 1970.

1970
M. Widner, I. Alexeff, W. D. Jones and K. E. Lonngren, "Ion Acoustic Wave
Excitation and Ion Sheath Evolution," The Physics of Fluids, Vol. 13, No. 10,
pp. 2532-2540, October, 1970.

1970

A. Hirose, I. Alexeff, W. D. Jones, S. T. Kush, and K. E. Lonngren, "Anomalous Resistivity in a Steady-State, Current-Carrying Discharge-Tube Plasma; Physical Review Letters, Vol. 25, No. 22, pp. 1563-1567, November, 1970.

1970

M. J. Lubin, W. Friedman, M. Roberts, and I. Alexeff, "Plasma Confinement in a High Magnetic Field Toroidal Quadrupole," The Physics of Fluids, Vol. 13, No. 12, pp. 3054-3056, December, 1970.

1970

W. L. Stirling and I. Alexeff, "A Turbulently Heated Electron Plasma," Plasma Physics, Vol. 12, pp. 489-502, Pergamon Press, 1970.

1971

K. Estabrook, I. Alexeff, W. D. Jones and K. E. Lonngren, "Reflection of Pseudowaves," The Physics of Fluids, Vol. 14, No. 1, pp. 185-187, January, 1971.

1971

A. Hirose and I. Alexeff, "Anamalously Rapid Skin-Current Penetration and Heating in Pulsed-Plasma Experiments," Physical Review Letters, Vol. 26, No. 16, pp. 949-952, April, 1971.

1971

M. Widner, I. Alexeff, and W. D. Jones, "Plasma Expansion into a Vacuum," The Physics of Fluids, Vol. 14, No. 4, pp. 795-796, April, 1971.

1971

K. Estabrook, M. Widner, I. Alexeff, and W. D. Jones, "Simulation of Pseudowaves and of Plasma Sheath Formation about a Grid by Computer Solution of the Ion Vlasov Equation," The Physics of Fluids, Vol. 14, No. 8, pp. 1792-1794, August, 1971.

1971

K. Estabrook, I. Alexeff, "Cherenkov Ion Acoustic Wave Radiation Generated by a Pseudowave," Physics Letters, Vol. 36A, No. 2, pp. 95-96, August, 1971.

1971

I. Alexeff, K. Estabrook and M. Widner, "Spreading of a Pseudowave Front," The Physics of Fluids, Vol. 14, No. 11, pp. 2355-2358, November, 1971.

1971

I. Alexeff, L. A. Berry, J. M. Dudley, K. G. Estabrook, A. Hirose, W. D. Jones, R. V. Neidigh, J. N. Olsen, F. R. Scott, W. L. Stirling, M. M. Widner, W. R. Wing, "Understanding Turbulent Ion Heating in the Oak Ridge Mirror Machine, "Burnout V," Plasma Physics and Controlled Nuclear Fusion Research, Vol. II, International Atomic Energy Agency, Vienna, 1971.

Igor Alexeff
Page 14

1972
K. E. Lonngren, W. F. Ames, H. S. C. Hsuan, I. Alexeff, and William Wing, "Self-Similar Solution of an RC Transmission Line," American Journal of Applied Physics, Vol. pp. 484-86, March, 1972.

1972
I. Alexeff and W. D. Jones, Production of Highly Stripped Heavy Ions in Hot-Electron Plasma Produced by and Electron Beam," IEEE Transactions on Nuclear Science, Vol. NS-19, No. 2, pp. 195-99, April, 1972.

1972
M. M. Widner, I. Alexeff, and W. D. Jones, "Langmuir Sheath Thickness as Observed by Ion Acoustic Waves and a Hot Probe," Journal of Applied Physics, Vol. 43, No. 4 pp. 1532-42, April, 1972.

1972
Igor Alexeff, "Spark Breakdown - An Electrostatic Criterion" 10th Annual Region III IEEE Conference, Knoxville, Tenn., April 1972.

1972
I. Alexeff, "Easily Observed Backward-Wave Line for Students," American Journal of Applied Physics, Vol. 40, pp. 763-64, May 1972.

1972
A. Hirose and I. Alexeff, "Higher-Temperature Limit for Turbulent Heating of Plasma by a Cross-Field Current," Physical Review Letters, Vol. 28, No. 18, pp. 1176-79, May 1972.

1972
I. Alexeff and Kent Estabrook, "A Critical Survey of Ion-Acoustic Wave Experiments and Theory," A3-1, Texas Tech. Lubbock - an invited paper.

1972
Kent Estabrook and I. Alexeff, "Nonexistance of Ion Waves and Landau Damping Driven Electrostatically in an Ideal Q Machine," Physics Review Letters, Vol. 29, No. 9, pp. 573-76, August, 1972.

1972
K. Estabrook and I. Alexeff, "Simulation of Ion-Acoustic Wave and Pseudowave Generation in a Plasma," The Physics of Fluids, Vol. 15, No. 12, pp. 2285-87, December, 1972.

1972
A. Hirose and I. Alexeff, "Electrostatic Instabilities Driven by Currents Perpendicular to and External Magnetic Field," Nuclear Fusion 12, pp. 315-23, 1972.

1972
I. Alexeff, "Instability Limit on Throughput for Calutron," ORNL-TM-4006, contract no. W-7405-eng-26, Oak Ridge National Laboratory.

1972
Lonngren, K. E., D. L. Landt, H. C. S. Hsuan, C. M. Burde, I. Alexeff, "Properties of Waves Defined by the Dispersion Relations D(K, Omega) = 1,: Physics of Ionized Gases, pp. 667-704, 1972.

1973
I. Alexeff, "Bypassing the Instability-Induced Throughput Limit in Calutron Isotope Separators," ORNL-TM-4116, Oak Ridge National Laboratory.

1973
Hirose, A. and I. Alexeff, "Electrostatic Instabilities Driven by Velocity Gradients," Physics of Fluids, Vol. 16, No. 7, 1973.

1973
I. Alexeff, "Throughput Limit in Mass Spectrograph-Type Isotope Separators," Journal of Applied Physics, Vol. 44, pp. 4592-94, Oct., 1973.

1974
I. Alexeff, J. Harris, C. Murphy, W. NamKung, M. Saylors, M. Pace, H. Ikegami, S. Aihara, M. Hosokawa, H. Aikawa, and S. Okamura, "Hot-Electron Plasma by Electron Cyclotron-Resonance Heating Followed by Magnetic Compression," Physical Review Letters, Vol. 32, No. 19, May 13, 1974.

1974
K. Longren, H. Hsuan, D. Landt, C. Burde, G. Joyce, I. Alexeff, W. Jones, H. Doucet, A. Hirose, H. Ikezi, S. Aksornkitti, M. Widner and K. Estabrook, "Properities of Plasma Waves Defined by the

Dispersion Relation $D(k, \ ) = 1$,"IEEE Transactions of

Plasma Science, Vol. PS-2, June 1974.

1974
Igor Alexeff, S. Peter Gary, and Howard W. Bloomber, "Reflection and Transmillion of Ion Acoustic Waves From a Plasma Discontinuity," PS-3, No. 2, pp. 46-48.

1975
Igor Alexeff, "A Theoretical Prediction of the Observed Plasma Heating in the Compression," IEEE Trans. on Plasma Science, PS-3, pp. 15-17, 1975.

1975
Igor Alexeff, H. J. Doucet, W. D. Jones, "Linear Ion Acoustic Waves in a Density Gradient," Vol. 17, No. 9, pp. 1738-1943, 1975.

1976
Igor Alexeff, H. Tamagawa, C. M. Jones, P. c. Miller, "Use of the Hot-Electron Mirror Machine Interem as a High-Z Ion Source," IEEE Trans. on Nuclear Science, Vol. NS-23, No. 2, April 1976.

1976
Igor Alexeff, O. Ishihara, "Landau Damping for Students Part III Boundary
Value Problem," IEEE Trans. on Plasma Science, Vo. PS-4, No. 1, March
1976.

1976
Igor Alexeff, O. Pocogelli, A. Hirose, "Refraction of Ion Acoustic Waves in
Thermal and Density Gradients Demonstrated Theoretically and
Experimentally," Proc. of 1976 TBILISSI Conf. in USSR.

1977
Igor Alexeff, J. T. Pytlinski, N. L. Oleson, "New Elementary Experiments
in Plasma Physics," 1977.

1977
Igor Alexeff, G. Pocobelli, A. Hirose, "Refraction of Ion Acoustic Waves in
Thermal and Density Gradients," Physcis Letters, 57A, No. 5453-54, 1977.

1977
Igor Alexeff, "A Critical Survey of Ion-Acoustic Waves."

1978
Igor Alexeff, "Critique on Isotope Separators," Journal of Applied Physics.

1978
Igor Alexeff, "Chance Look and Striking Photograph," The Oak Ridger,
Page 1, Column 8, December 26, 1978.

1978
Igor Alexeff, Osamu Ishihara, H. J. Doucet, W. D. Jones, "Reflection and
Absorption of Ion-Acoustic Waves in a Denisty Gradient," Physics of Fluids,
1978.

1978
Igor Alexeff, Osamu Ishihara, "Landau Damping for Students," IEEE Trans.
on Plasma Science, Vol. PS-6, pg. 212, June 1978.

1978
Igor Alexeff, "Instability Limit on Throughput for Calutrons," IEEE Trans.
on Plasma Science, Vol. PS-6, 1978.

<u>RESUME</u>

Francis Frederick Dyer
Electrical Engineering Department
The University of Tennessee
Knoxville, TN 37996-2100

I. <u>PERSONAL</u>

Birthdate: April 4, 1953
Marrital Status: Married
Health: Excellent

II. <u>EDUCATION</u>

1. The University of Tennessee, Knoxville. Bachelors Degree in Electrical Engineering, 1976.

2. The University of Tennessee, Knoxville. Course work toward Masters Degree in Electrical Engineering, 1976 - 1978.

III. <u>EMPLOYMENT RECORD</u>

1972 - 1976	NASA, Kennedy Space Center, Florida. Co-op program. Audio and television system design.
1976 - 1979	The University of Tennessee, Knoxville. Graduate Teaching Assistant. Taught Laboratories in Plasma, Electronics, Electromagnetic fields and communications, Power systems and circuits.
1979 - Present	The University of Tennessee, Knoxville. Research Associate, Orbitron Maser project supported by the U.S. Air force. Design and construct millimeter wave apparatus and electronic instrumentation.

IV. OTHER PROFESSIONAL EXPERIENCE

In collaboration with prof. Igor Alexeff, I have done extensive laboratory work in plasma engineering. Major areas of interest include improved light sources, high power opening switches, and millimeter waves. Much of this work was supported by the National Science Foundation.

I have also completed many short term consulting projects in a wide range of topics. Some examples are:

1. Designed an updated and improved version of a metal identification device for Salvonics, Inc. of Oak Ridge, Tenn. This instrument is now in commmercial production.

2. Built a 40 KV test facility to investigate power line safety.

3. Conducted an extensive study of electric blanket failure modes that could cause a fire.

4. Designed an electronic control circuit for arc welding.

5. Tested improved electric motor designs for Motor Magnetics, Inc.

RECOMMENDATION

Fred Dyer has been associated with me (Igor Alexeff) for some time now, first as a student, now as a research engineer. He has been a co-inventor and co-discoverer of several major inventions and discoveries. He shows enormous bursts of technical insight, and has been responsible for several major devices being made to work.

I personally feel that Fred is indespensible if our projects are to move forward rapidly and effectively, and wish him to stay at U.T. Knoxville in the status of Assistant Research Professor. Unlike a regular professor, Fred can then devote full time to research - with no teaching.

Igor Alexeff
Principal Investigator

54

PROFESSIONAL RESUME

J. Reece Roth
Department of Electrical Engineering
The University of Tennessee
Knoxville, Tennessee 37996-2100
(615) 974-4446
FTS 855-4446

I. **Personal**

Birthdate: September 19, 1937
Marital Status: Married, two children
Health Status: No physical handicaps or health problems

II. **EDUCATIONAL**

College: Massachusetts Institute of Technology, graduated in June 1959 with a S.B. in Physics.

Graduate: Entered Cornell University in September 1959, graduated in June 1963 with the Ph.D. Major: Engineering Physics. Minor subjects: Magnetohydrodynamics and Astrophysics.

III. **PROFESSIONAL EXPERIENCE**

1. Summer 1957, Engineering Aide at Aerojet-General Corporation, Azusa, California. Carried through a study of the electromagnetic flowmeter as a means of measuring the exhaust velocity of rocket engines.

2. Summer 1958, worked as an Engineering Aide at Aerojet-General with the Rover Project (the nuclear rocket propulsion program).

3. Summer 1959, worked as an Aerospace Engineer with the electrical propulsion group at Rocketdyne, a division of North American Aviation.

4. 1963 to 1978, Member of the Plasma Physics Branch of the Physical Science Division at the NASA Lewis Research Center in Cleveland, Ohio. Was Principal Investigator of the NASA Lewis Bumpy Torus Project.

5. September 1978 to June, 1982. Visiting Professor of Electrical Engineering, University of Tennessee, Knoxville. Principal Investigator of two research contracts in the field of electric field dominated plasma, one with the ONR, the other with AFOSR. These contracts provided half-time support for the Principal Investigator and 4 Research Assistants. A third contract with TVA provided support for one graduate student for studies in the field of fusion energy, and retainer-type consulting for the Principal Investigator. In addition to research, taught a junior level course on plasma engineering, a graduate

sequence on fusion technology, plasma diagnostics, and physics of fusion, also taught one-week minicourses on fusion energy and fusion diagnostics.

6. June 1982 to August, 1983. Research Professor, Department of Physics. Continuation of contract research, and teaching of graduate sequences in fusion energy and plasma physics.

7. September 1983 to present. Professor of Electrical Engineering. continuation of contract research, at a level of about $170,000 per year, and teaching of graduate course sequence in Fusion Energy and junior-level course in Plasma Engineering. Is presently preparing a textbook, "Introduction to Fusion Energy" with two co-authors.

IV. HONORS, AWARDS, AND LISTINGS

Relevant student honors include a four-year Alfred P. Sloan Scholarship at M.I.T., Presidency of the M.I.T. Rocket Research Society, the 1957 American Rocket Society-Chrysler Corporation's Student Award, and a Ford Fellowship at Cornell. Life Member of Sigma Xi, Fellow of IEEE, and co-recipient of one of NASA's "Awareness" awards to the Bumpy Torus Project. Listed in "Who's Who in the Midwest," 1970 to 1978 Editions, and in "Who's Who in the South and Southwest,"17th Edition, Who's Who in America, 43rd Edition, American Men & Women of Science, 15th Edition, and Who's Who in Engineering, Fourth Edition.

V. PROFESSIONAL SOCIETY MEMBERSHIPS

1. Fellow of the IEEE
2. Life member of Sigma Xi
3. Life member of the AAAS
4. Member of the American Physical Society
5. Member of the AIAA
6. Member of the American Nuclear Society
7. Member of American Society for Engineering Education
8. Member of the IEEE Nuclear and Plasma Sciences Society
9. Member of the Archaeological Institute of America

VI. PROFESSIONAL SOCIETY ACTIVITIES

1. Associate Editor, IEEE Transactions on Plasma Science, 1973-Present.
2. Elected Member-at-Large of Administrative Committee, IEEE Nuclear and Plasma Sciences Society, 1974-77.
3. Secretary, NPSS Administrative Committee, 1975.
4. Organizing Committee, IEEE Plasma Science and Applications Committee, 1971-73.
5. Elected Member, Executive Committee of IEEE Plasma Science and Applications Committee, 1974-77, 1980-82.

6. ...ember of the Program Committee, IEEE International Conferences on Plasma Science, 1974, 1975.
7. Member, Executive Committee, Northern Ohio Section of the American Nuclear Society, 1975-1978.
8. Member, AIAA Plasmadynamics Technical Committee, 1979 to 1981.
9. Director, and Member of Executive Committee, East Tennessee Section of the IEEE, 1982-83.
10. Vice Chairman and Chairman-Elect, East Tennessee Section of the IEEE, 1983-84.

VII. PROFESSIONAL ACOMPLISHMENTS

In the past twenty years, Dr. Roth has authored or co-authored 84 publications, of which 36 were articles in refereed journals, and the remainder of which were internally reviewed NASA reports. Dr. Roth has published in the Physics of Fluids, the Review of Scientific Instruments, the IEEE Transactions on Plasma Science, Physical Review Letters, Plasma Physics, Nuclear Fusion, the Journal of Applied Physics, the Journal of Fusion Energy, the Journal of Nuclear Instruments and Methods, the Journal of Spacecraft and Rockets, Nuclear Technology/Fusion, the Journal of Mathematical Physics, Nature, and elsewhere. In addition to these publications, Dr. Roth has been author or co-author of 81 oral or poster presentations at professional society meetings, nearly all of which report experimental data on his scientific or engineering work. These 81 presentations include 25 full-length papers published in conference proceedings.

While at the NASA Lewis Research Center, Dr. Roth made two pioneering contributions to fusion-related superconducting magnet technology. He was responsible for the basic design and distinctive features of the "Pilot Rig" superconducting magnet facility at NASA Lewis in Cleveland. This facility went into service in December, 1964, and was the first such facility ever to be used for plasma physics or controlled fusion research. Dr. Roth's second contribution in the magnet area was as the engineer responsible for the basic design and distinctive features of the NASA Lewis superconducting bumpy torus magnet facility. This facility went into service in 1972, and was the first superconducting magnet facility anywhere in the world to generate a toroidal magnetic field.

In studying the plasma which these facilities were designed to confine, Dr. Roth discovered two previously unrecognized modes of plasma instability. The first of these is the "continuity-equation oscillation" (the name is Dr. Roth's own) which was observed in the Pilot Rig in 1967. Dr. Roth was the first to investigate this oscillation experimentally, and the first to describe it theoretically. His work on the continuity-equation oscillation has been recognized in standard monographs and compilations such as A. I. Akhiezer et al. Plasma Electrodynamics, and F. Cap's Handbook on Plasma Instabilities, Vol. 1. Dr. Roth was also the first to report the experimental observation of the "Geometric Mean Plasma Emission" (Dr. Roth also named this instability). His data were explained theoretically by Professor Igor Alexeff, and they jointly reported the discovery of this new instability in August, 1979.

Dr. Roth initiated research on the electric field bumpy torus concept, an approach to creating a plasma of fusion interest in which strong radial electric fields are imposed on a bumpy torus plasma, in such a way that they contribute to the heating, stability, and confinement of the plasma.

Dr. Roth has authoritative knowledge of Penning discharges; the use of superconducting magnet facilities in plasma and fusion applications; the continuity-equation oscillation and moving striations; ion heating and transport in a modified Penning discharge; high temperature plasma physics; fusion energy; and fusion technology. Dr. Roth was the first to identify the physical mechanism responsible for ion heating in a modified Penning discharge, and the first to describe it. Dr. Roth's academic responsibilities have included teaching a required undergraduate course on plasma engineering from his own notes, a three-quarter graduate sequence on fusion energy, also from his own notes, a three-quarter doctoral level course on plasma physics, and intensive one-week minicourses on Fusion Diagnostics and Fusion Energy, which have attracted students from all over the United States and Canada.

APPENDIX B

Pertinent Literature

A Simple High-Voltage Opening Switch Using Spoiled Electrostatic Confinement[1]

IGOR ALEXEFF, SENIOR MEMBER, IEEE, AND FRED DYER

Abstract—We have initiated and sustained a plasma discharge at pressures well below the Paschen minimum by trapping electrons in orbits around a positively charged wire. Spoiling the trapping process terminates the discharge and opens the circuit in spite of high voltage applied.

WE HAVE DEVELOPED a fast opening high-voltage switch by using electrons trapped in orbits around a positively charged wire. Such trapping procedures have been used before to create a low pressure discharge [1], to improve vacuum pump performance [2], and to improve vacuum ion gauges [3], [4]. The basic idea in this trapping procedure is that an electron is generally produced by ionization with some finite velocity, or equivalently, with some angular momentum relative to the wire, and so tends to go into orbit around the wire. End confinement is provided by supplementary negative end electrodes. Experimentally, we find that the mean free path of such trapped electrons can be many meters. Applying a positive high voltage to the central wire results in a rapid breakdown, presumably starting from random ionization in the apparatus.

Our original contribution is to provide a switchable end electrode as shown in Fig. 1. If the electrode is held at cathode potential, the orbiting electrons are reflected, a long mean free path for electrons occurs, and the discharge ignites and is sustained at a voltage drop of about 200 V. On the other hand, if the end electrode is connected to the anode, the orbiting electrons are absorbed, and the discharge immediately goes out—the circuit is opened.

Theoretically, the opening time is given by the deionization time of the plasma, which is on the order of the flight time of ions to the wall. This time τ (in seconds) is given by

$$\tau = l \left(\frac{KT_i}{m_i} \right)^{-1/2}$$

where l is the radius of the tube (meters), K is Boltzmann's constant (Joules per degree Kelvin), T_i is the ion temperature (degrees Kelvin), and m_i is the ion mass (kilograms). In our switch operating with argon, τ is about 10 μs. Experiments do reveal a switching time comparable to the above value.

Experimentally, a typical model has the following characteristics. The cathode is formed of a cylinder of aluminum foil about 6 in long and about 2 inches in inner diameter. The
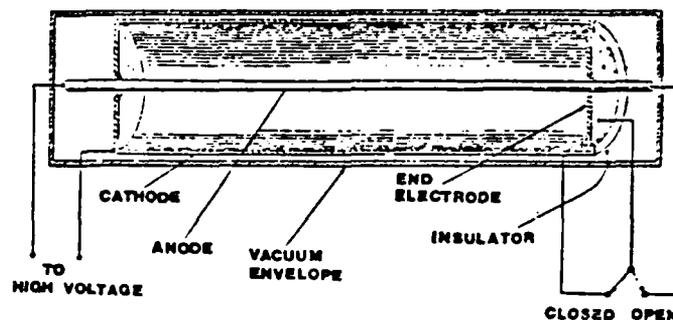
Fig. 1. Schematic of opening switch.

anode is a tungsten wire having a diameter of 0.005 in. The chamber is evacuated to a pressure of 10^{-5} torr. The aperture in the control end plate is about $\frac{1}{8}$ inch in diameter. The plasma switch is employed to extinguish an arc across a mechanical switch which has 500 mA of direct current flowing there—through and at opening 2 kV is developed across the switch contacts. The foregoing described embodiment has been employed also to extinguish the arc across mechanical switch contacts in a circuit with a voltage of 10 kV. At switching voltages above 10 kV, breakdown occurs over the external surface of the insulators. It will be recognized, however, that substantially larger cathodes and anodes may be employed.

The plasma switch requires a switching current to the control plate of only about one to five percent of the main discharge current. The ratio of switching current to main current can be reduced by reducing the diameter to length ratio of the cathode. We feel that this electrostatic plasma switch is less expensive and less complex than the prior art devices and switches faster. Our basic competitor we feel to be the Hughes cross field switch tube [5] which has the basic disadvantage of initiating switching by energizing and deenergizing a large solenoid. In this case, the switching time is limited by the inductive rise time. Of course, we recognize that our device does not handle much voltage and current at present. However, it is a prototype test device, and we feel that it can be scaled up easily in the future.

REFERENCES

[1] G. W. McClure, *Appl. Phys. Lett.*, vol. 2, p. 233, 1963.
[2] I. Alexeff and E. C. Peterson, in *1955 Vacuum Symp. Trans.*, Committee on Vacuum Techniques, Inc., 1956, p. 87.
[3] R. H. Hooverman, *J. Appl. Phys.*, vol. 34, p. 3505, 1963.
[4] W. G. Mourad, T. Pauly, and R. G. Herb, *Rev. Sci. Instr.*, vol. 35, p. 661, 1964.
[5] H. Gallagher, C. Hofmann, and M. Lutz, *IEEE Trans. Power App. Syst.*, vol. PAS-92, p. 702, Mar./Apr. 1973.

MILLIMETER MICROWAVE EMISSION FROM A MASER BY USE OF PLASMA-PRODUCED ELECTRONS ORBITING A POSITIVELY CHARGED WIRE

Igor Alexeff and Fred Dyer

49

Millimeter Microwave Emission from a Maser by use of Plasma-Produced Electrons Orbiting a Positively Charged Wire

Igor Alexeff and Fred Dyer

University of Tennessee, Knoxville, Tennessee 37916

Plasma-produced electrons have been trapped for long periods of time in orbits around a positively charged wire. Since the frequency of rotation of each electron increases if it loses kinetic energy and sinks into the positive-potential well, phase bunching resulting in intense microwave emission can be easily excited.

The basic advantages of this electrostatic microwave emitter over magnetically confined electron devices is that theoretically by use of readily available voltages and wire sizes, it can operate at free-space wavelengths down to at least 0.1 mm. However, limits in available magnetic field strength restrict conventional magnetic-field devices to wavelengths above 1.0 mm. In addition, since the orbit frequency is a function of electron energy, relativistic electrons are not required for operation.

The basic concept of trapping plasma-produced electrons in orbit around a wire is not new. The first publication which appeared on the subject was by McClure[1] in 1963. Other papers concerned the trapping of electrons around grid wires in Evapor-Ion vacuum pumps,[2] and the Orbitron ion gauges.[3,4] Based on this earlier work, we propose the name "Orbitron" microwave source[5] for our device. The basic idea that the device could be used as a high-frequency maser grew out of plasma-wave and maser studies in our laboratory, and a previous device in which an electric field was used to distort electron orbits in a magnetically confined electron cloud was successfully operated.[6]

The basic principle of operation of any maser is that electrons oscillate in a system in which the electrons both are confined for a long time and in which the electron frequency varies with energy. Electrons interacting with the noise field in a microwave cavity gain or lose energy, experience a frequency shift, drift in phase, and after some latent period, "phase bunch" and release a coherent burst of radiation. In a conventional atomic maser, the frequency variation with energy is apparent from the differently spaced quantum levels. In a free-electron maser using electrons trapped in a uniform magnetic field, the frequency is independent of energy, and maser action cannot occur. However, maser action can occur if the electrons are made relativistic, so that the relativistic change of mass with energy produces a frequency shift with changing electron energy.[7] In our maser, electrons are trapped radially by a balance between the electric field and centrifugal force. Axially, the electrons are trapped by a carefully designed fringing field.[1] This good trapping produces a mean free path of many meters, and results in our obtaining a sufficiently long "latent period" to permit phase bunching to occur. Previous work with electrons orbiting electrostatically used a quite different physical arrangement: an electron gun, an electron collector, and a single-pass electron beam.[8]

Our mathematical model is that of a group of electrons, produced from a glow discharge, each in a circular orbit with an initial angular frequency ω_0. The electrons do not interact with each other ($\omega_{pe} < \omega_0$), but with an external cavity field (here simulated by a resistive layer). If an electron clump occurs due to random fluctuations, it creates a local electric field that drags an image charge along in the resistive medium (simulating radiation resistance). The electron clump loses kinetic energy, moves inward in radius, increases in angular velocity, and overtakes more slowly rotating electrons ahead. Now the clump grows, the drag increases, and finally most of the electrons are swept up into a coherently rotating and emitting radial spoke. Since the electrons are moving at an angular velocity ω higher than their initial angular velocity ω_0, the emission occurs at a higher frequency than the initial orbital frequency ($\omega > \omega_0$). Since the power radiated by a group of coherently oscillating electrons goes as the square of the number of electrons, the power radiated can be large. In this preliminary calculation, electrons are assumed to be electrostatically trapped—hence ions would be electrostatically ejected and are

not treated. In addition, since we suspect the action to occur close to the surface of the wire, only circular orbits are treated.

In our work, a theoretical study of the instability was done first. The mathematical results use the standard beam-plasma treatment[9] adapted to cylindrical coordinates, and are tabulated below:

$$\omega_0 = \frac{1}{r}\left(\frac{-Z_e eV_r}{m_e \ln(r_2/r_1)}\right)^{1/2}, \tag{1}$$

$$\omega = \omega_0 \pm \left(\frac{1}{\sqrt{2}} + \frac{i}{\sqrt{2}}\right)\omega_0^{3/2}\beta, \tag{2}$$

$$\beta = \frac{-Z_e eRn_e}{4\pi^2 V_r}\ln\left(\frac{r_2}{r_1}\right). \tag{3}$$

In Eq. (1), ω_0 yields the angular frequency of rotation at radius r around a wire of radius r_1 charged to a positive potential V_r. $Z_e e$ is the sign and magnitude of the electron charge, m_e is the electron mass, and r_2 is the effective cutoff distance of the electric field due to electron screening. Although r_2 is not well defined, it lies in a logarithmic term, and so is not a sensitive parameter. All units are MKS.

In Eq. (2), we find the emission frequency of an electron interacting with an external structure (described below). We find that if we choose a positive solution (gain), we obtain a real angular frequency somewhat above ω_0. Note that the growth rate peaks sharply at the highest possible value of ω_0, that for electrons just grazing the surface of the wire.

In Eq. (3), we compute the factor giving growth rate. Here, we simulate radiation resistance by placing our orbiting electrons between two resistive, concentric cylinders. Here R is the resistance in ohms per turn, where $R \approx 2\pi r\rho(l\Delta r)^{-1}$. Here r is the average radius of the two cylinders, ρ is the resistivity of the shell medium (Ω m), l is the axial length of the cylindrical structure, and Δr is the sum of the thicknesses of the two cylinders. The number of electrons in the orbiting shell between the resistive cylinders n_e is the total number of electrons contained. As is characteristic of resistive instabilities, the larger the resistance R or the number of electrons n_e, the greater the instability growth rate.

Experimentally, we find that the device emits microwaves only if a high-Q cavity resonator is placed around the wire (see Fig. 1), and if the discharge current is raised above a critical threshold. [An aluminum beer can has been
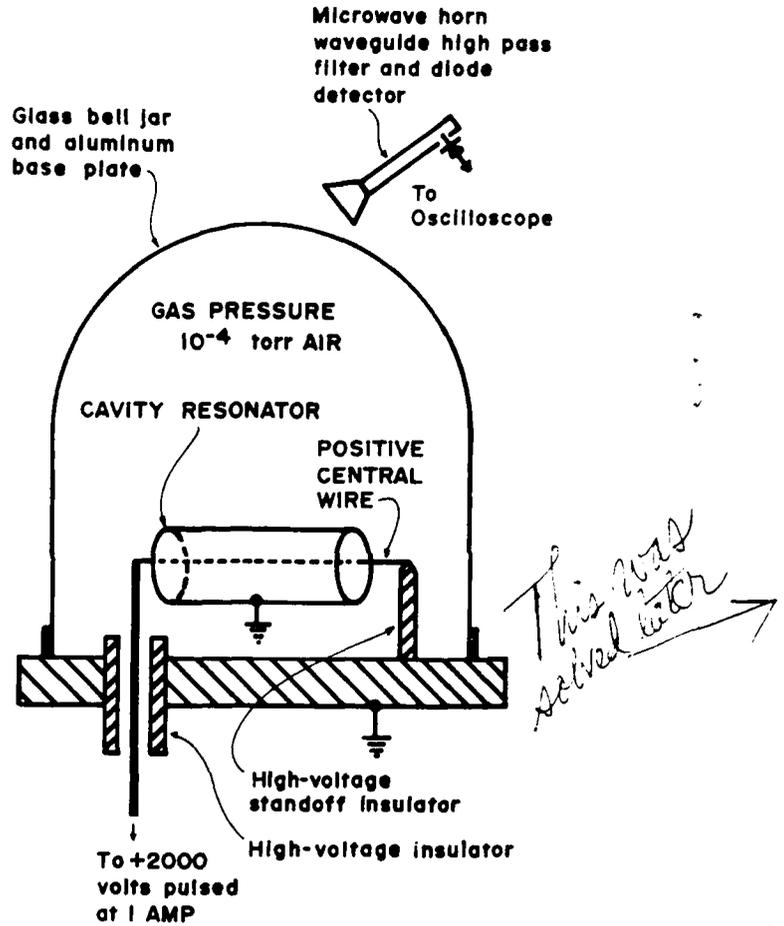
FIG. 1. Schematic of a typical microwave emitter. Microwaves are easily observed outside the bell jar at some distance, and can be focused, reflected, diffracted, etc.

found to be an excellent cavity if holes for the wire are drilled to extract the beer and the tab is not pulled.][10] Applying about 2000 V in a square-wave pulse results in the following behavior. First, the discharge current gradually builds up over about 50 μs. This time decreases with increasing gas pressure and quantitatively is consistent with the buildup of an ionizing electron cloud by a rotating electron avalanche.

Next, an intense microwave burst is emitted for about 20 μs. The radiation, as shown in Fig. 2 escapes from the cavity via the central wire, and the radiation intensity and polarization pattern is consistent with the wire acting as a simple antenna. A typical measured peak power output for emission at 3 cm wavelength is several watts— or 100 times that of our test Klystron. The pulse is fairly noisy, for unknown reasons.
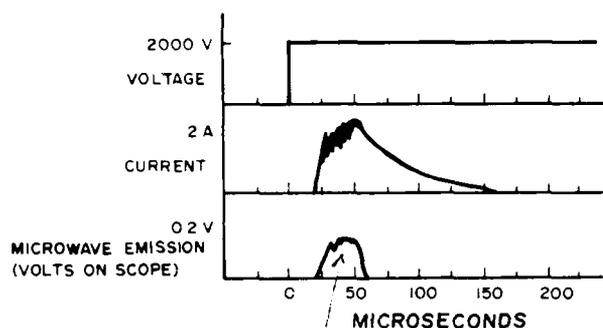
FIG. 2. Operation during voltage pulse. The current dies out on this graph because the supply was a small charged capacitor.
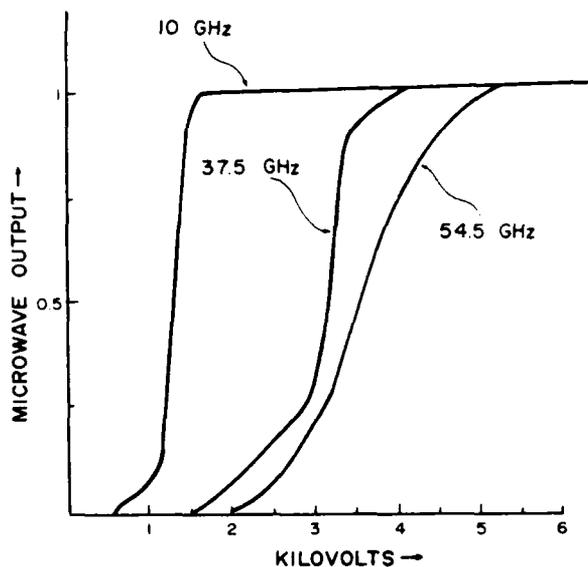
noise due to ω_{pi} ?

Finally, the microwave emission terminates, although the discharge current continues. Attempts to produce dc operation so far have resulted only in a chain of pulses. The reason for the rf termination is unknown at present.

We have checked the dependence of the emitted frequency on wire size and applied voltage, and have obtained reasonable agreement with Eq. (1). By using diode detectors, and waveguides as high-pass filters,[11] we obtained the increase of frequency with applied voltage as shown in Fig. 3. Data were taken at 3 cm, 8 mm, 5.5 mm, and 4 mm (the last not shown). Note that the filters were high pass only, so that we do not know if the lower-frequency emission persists as the voltage is increased. At present, the only restriction on working at still shorter wavelengths is the lack of diagnostic apparatus. In any case, the observation of the predicted dependence between frequency and voltage supports the validity of our model.

$P(\omega)$

The radio-frequency emission we observe cannot be due solely to plasma effects, because the plasma frequency ω_{pe} that we compute is far too low for our observed frequencies. We estimate the electron plasma density as follows. First, using the observed glow diameter around the wire in the steady state, we estimate the radius of the electron cloud orbiting the wire. A second limit on this radius is given by the rate of gas flow to the wire. If the radius were too small, the rate of gas ionization would be insufficient to provide the observed current. Knowing the radius of the electron cloud, and computing the amount of charge it contains on the basis of charge balance, we compute n_e and hence ω_{pe}. An independent measure of the charge contained in orbit around the wire was obtained by switching one end elec-

FIG. 3. Graph of normalized microwave detector output vs discharge voltage, showing frequency dependence on voltage.

trode positive, sweeping out the total orbiting electron cloud, and collecting and measuring it. In all cases ω_{pe} was lower by at least a factor of 10 than the observed emission frequency. If the noise (Fig. 2) accompanying microwave emission is attributed to the ion plasma frequency, then a value for ω_{pe} is obtained that agrees with those discussed above.

maybe

One interesting concept is in the use of many (n) wires in the same cavity. If our maser model is correct, the orbiting electrons around each wire should phase lock with the cavity field, and the emitted radiation power should increase as n^2. Preliminary experiments seem to demonstrate this effect. However, use of the wrong spacing also is observed to produce destructive interference. By a proper arrangement of many wires in a large cavity we may be able to produce intense microwave emission in the submillimeter range.

n^2 power!

In addition to the microwave emission properties of the orbiting electron device, it has many additional technical and scientific interests. For example, we have found that by interrupting the good electron confinement of the orbiting electrons, we can extinguish a high-voltage discharge, creating a high-voltage opening switch.[12] The collective interactions of electrons and ions in this magnetic-field-free region offer many opportunities for basic plasma research. Finally,

since the positive wire repels positive ions, it is not subject to positive-ion sputtering, and is found to have a long lifetime.

---

[1]G. W. McClure, Appl. Phys. Lett. 2, 233 (1963).

[2]I. Alexeff and E. C. Peterson, *1955 Vacuum Symposium Transactions* (Committee on Vacuum Techniques, Inc., Boston, 1956), Vol. 2, p. 87.

[3]R. H. Hooverman, J. Appl. Phys. 34, 3505 (1963).

[4]W. G. Mourad, T. Pauly, and R. G. Herb, Rev. Sci. Instrum. 35, 661 (1964).

[5]"Orbitron" name proposed with the permission of R. G. Herb, inventor of the Orbitron ion gauge.

[6]L. R. Barnett and I. Alexeff, in *Proceedings of the IEEE International Electron Devices Meeting, Washington, D. C., 1979* (Institute of Electrical and Electronics Engineers, New York, 1979), Technical Digest No. CH-1504-0/79/000-0/68.

[7]J. L. Hirshfield and V. L. Granatstein, IEEE Trans. Microwave Theory Tech. 25, 527 (1977).

[8]A. V. Gaponov, M. I. Petelin, and V. K. Yulpatov, Izv. Vyssh. Uchebn. Zaved., Radiofiz. 10, 1414–1453 (1967) [Radiophys. Quantum Electron. 10, 794–813 (1967)].

[9]J. R. Pierce, *Traveling-Wave Tubes* (Van Nostrand, Princeton, N. J., 1950), Chap. 16.

[10]An all-aluminum can is needed to avoid iron with its residual magnetic effects and short, q-reducing skin depth.

[11]Microwave diagnostic equipment loaned to us by Owen Eldridge, Alan England, Marshall Loring, and John Wilgen of the Oak Ridge National Laboratory.

[12]Igor Alexeff, U. S. Patent Application No. 67 467 (1979), and "A Simple High-Voltage Opening Switch using Spoiled Electrostatic Confinement," IEEE Trans. Plasma Sci. (to be published).

53

Steady-State, High-Vacuum
Operation of the Orbitron Maser.*

Mark Rader, Fred Dyer, and Igor Alexeff
University of Tennessee 37996-2100

We have operated our Orbitron Maser[1] in a high vacuum of 2×10^{-6} torr produced by an oil diffusion pump trapped by a liquid-nitrogen-cooled baffle. Electrons are supplied by an oxide-coated tungsten hot cathode placed inside the cylindrical cavity. To demonstrate that no plasma was present to produce plasma oscillations, as claimed by Schumacher and Harvey[2,3] we monitored the presence of plasma in the open cavity. The plasma-free emission corresponded to harmonically-related, steady-state, narrow lines. The fundamental (lowest frequency) line corresponded to a resonance in the cavity system, which could be observed with a grid-dip meter. The highest frequency line corresponded to 10GHz, which is about the frequency of an electron just grazing the wire in a circular orbit at the voltage used (600 volts).

To obtain these results, we use multiple anode wires (up to 7) to increase the space-charge limited current. Apparently, mode-locking between electrons on adjacent wires occurs. We have also been able to frequency-tune (pull) the resonant lines by adjusting anode voltage. Finally, we have suppressed the lower-frequency lines by excluding large-orbit electrons from the device.

TYPICAL HIGH FREQUENCY ORBITRON SPECTRUM

10dBm/div.

2.6 Ghz   4.7 Ghz

In our pulsed gas-filled tubes, a much higher voltage can be used, as well as a thinner wire. In this mode of operation, sub-millimeter operation is routine, and we have obtained radiation[4] at 1 THz (0.3mm). Peak microwave power output is about 1.5 watts at 1 THz and about 50 watts at frequencies up to 100 GHz. Efficiency ranges from 10% at 3.5 GHz to 1×10^{-3}% at 1 THz.

1. I. Alexeff and F. Dyer, Phys. Rev. Lett. 45, 351 (1980).
   I. Alexeff, IEEE Trans. Plasma Sci. PS-12, 280 (1984).
   I. Alexeff, Phys. Fluids, 28, 1990, June, 1985.

2. R.W. Schumacher and R.J. Harvey, 1984 IEEE International Conference on Plasma Science, Conference Record, P 109, IEEE Publication No. 84CH 1958-8.

3. R.W. Schumacher and R.J. Harvey, Bull. A.P.S., 29, 1179, October, 1984.

4. Igor Alexeff, Fred Dyer and Wlodek Nakonieczny, International Journal of Infrared and Millimeter Waves. p. 481, 6, (7) 1985 (Plenum).

Abstract Submitted for the Twenty-Eighth Annual Meeting
Division of Plasma Physics
November 3-7, 1986

Category Number and Subject __4.9 Coherent Radiation Generation__

☐ Theory   ☒ Experiment

Constant Frequency Plasma Oscillations*, FRED DYER, MARK RADER, and IGOR ALEXEFF, University of Tennessee 37996-2100 -- We have been observing a new and previously undetected steady-state spectral line being emitted from a device with the same basic design as our pulsed orbitron maser.[1] Upon investigation of these spectral lines we found that the fundamental (lowest frequency) line was the stable steady-state emission of the electron plasma frequency (ω_p). We believe that this frequency stability is caused by the continual flushing of ions from the system and their subsequent replacement by new ions. This flushing damps the instabilities, which cause the frequency drift seen in other ion plasma oscillators, before they form.

1. I. Alexeff and F. Dyer, Phys. Rev. Lett. 45, 351 (1980); I. Alexeff, Phys. Fluids, 28, 1990, June.1985.

☐ Prefer Poster Session

☐ Prefer Oral Session

☒ No Preference

    Special Requests for Placement of this Abstract:_____

    Special Facilities Requested (e.g., movie projector):_____

Submitted by:

(Signature of APS Member)

Igor Alexeff
(Same Name Typewritten)
Department of Electrical Engineering
University of Tennessee, 37996-2100
(Address)

This form, or a reasonable facsimile, plus TWO XEROX COPIES, must be received by NO LATER THAN NOON, Friday, July 18, 1986, at the following address:

Ms. Dana Richards
L-630
Lawrence Livermore National Laboratory
P. O. Box 5511
7000 East Avenue
Livermore, CA 94550
(415) 422-9858

Category Number and Subject 4.9 Coherent Radiation Generation

☐ Theory   ☒ Experiment

Steady-State Operation of the High Vacuum Orbitron Maser[*],
MARK RADER, FRED DYER, and IGOR ALEXEFF, University of
Tennessee 37996-2100 -- We have operated our radial injection orbitron
at a pressure of 1×10^{6} torr[1]. Electrons are supplied to this system by
means of an axial, oxide-coated hot tungsten filament. The plasma-free
emission of this device corresponded to harmonically-related, steady-
state, narrow lines unlike the results obtained by others[2]. Depending
upon the device's design, the fundamental (lowest frequency) line
corresponded either to a external resonance, or to a TEM cavity mode.
Operation of these devices is routine in the 0 - 2 GHz frequency range.
Frequencies as high as 1.5 GHz have been observed at the low operating
voltage of 40 volts. To obtain these results, we have used multiple anode
wires (up to 7) to increase the space-charge limited current, and apparent
mode-locking between electrons orbiting adjacent wires occurs.

1. I. Alexeff and F. Dyer, Phys. Rev. Lett. 45, 351 (1980); I. Alexeff,
Phys. Fluids, 28, 1990, June 1985.
2. R. W. Schumacher and R. J. Harvey, Bull. A.P.S., 29, 1179, October,
1984.

☐ Prefer Poster Session

☐ Prefer Oral Session

☒ No Preference

Special Requests for Placement of
this Abstract:_____

Special Facilities Requested (e.g., movie
projector):_____

Submitted by:

Igor Alexeff (signature)
(Signature of APS Member)

Igor Alexeff
(Same Name Typewritten)
Department of Electrical Engineering
University of Tennessee   37996-2100
(Address)

This form, or a reasonable facsimile, plus TWO XEROX COPIES, must be received by NO LATER THAN NOON,
Friday, July 18, 1986, at the following address:

Ms. Dana Richards
L-630
Lawrence Livermore National Laboratory
P. O. Box 5511
7000 East Avenue
Livermore, CA 94550
(415) 422-9858

A simplified Vlasov–Landau treatment of electron motion in the orbitron maser

Igor Alexeff

Department of Electrical Engineering, The University of Tennessee, Knoxville, Tennessee 37996-2100

An electron ring trapped in a logarithmic potential well (orbitron) is studied. The electrons in the ring possess a spread in angular velocity. A forward traveling-wave line is used to simulate a cavity resonator. For a Maxwellian, or monotonically increasing electron distribution function with increasing orbital frequency, sinusoidal perturbations are damped. For an inverted energy distribution, they grow. The growth rate at harmonics of the orbital frequency increases linearly with harmonic number.

I. INTRODUCTION

The orbitron maser originated with considering electron motion about a positive charged wire.[1] For the proper initial injection conditions, the electrons perform circular orbits around the wire. Mathematical analysis shows that these orbits are negative-mass unstable.[1] By this we mean that if an electron loses kinetic energy to a rf field, it drops deeper into the potential well surrounding the wire, increases its angular velocity, and overrides in phase unperturbed electrons. Finally, the process causes the electrons to bunch into a rotating radial spoke that radiates coherently. More detailed computations show that all classes of orbits exhibit the instability.

The most interesting feature of the orbitron maser is its frequency of operation. The electron frequency for a wire 1/40 mm in diameter charged to 10 kV, corresponds to a free-space wavelength of 1 mm. This is much shorter than that corresponding to a conventional cyclotron maser, as a magnetic field of 10 T is required for 1 mm operation. The orbitron, however, has no applied magnetic field. However, it is much longer than the wavelengths easily reached by conventional lasers and masers.

Numerous devices have been made in our laboratory consisting of positive wires with orbiting electrons placed in cavity resonators. These devices have produced microwave radiation from 0.1 to 600 GHz. Power output is about 50 W from 10 to 100 GHz, and 10 W at 300 GHz. An optimized device at 30 GHz has a measured efficiency of about 5%. At the lower frequencies, 1.0 to 10 GHz, a device can be operated in a narrow-band, cw, tuneable mode. Above this frequency, higher voltages are required, and operation has been pulsed for several microseconds of operation, primarily because of high-voltage breakdown problems.

II. THEORY FOR A RING OF ELECTRONS

In this paper, we use a simplified model to provide insight into orbitron operation. We consider a circular ring of electrons trapped in a radial electric field derived from a logarithmic potential well. No applied magnetic field is present. The electron orbital frequency is given by

$$\omega_0 = \frac{v}{r} = \frac{1}{r}\left(\frac{-ZeV_0}{m\,\ln(r_2/r_1)}\right)^{1/2}. \tag{1}$$

Here ω_0 is the electron orbital frequency (rad/sec), v is the linear electron velocity in orbit (m/sec), r is the radius of the electron orbit (m), Z is the sign of the electron charge (-1), e is the magnitude of the electron charge $(1.60 \times 10^{-19}\,\mathrm{C})$, m is the mass of the electron $(0.91 \times 10^{-30}\,\mathrm{kg})$, V_0 is the voltage applied to the inner conductor (V), and r_2 and r_1 are the radius of the outer and inner conductor, respectively (m). A spread in orbit radius r will later provide us with a spread in angular frequency, ω_0.

A second simplified model is to use a forward-wave line to simulate a cavity resonator, as shown in Fig. 1. We assume that the line supports the dc electric field that contains the electron ring, but interacts with the ac fields produced. The justification for use of a line instead of a cavity resonator is that an oscillating rf electric field in a cavity resonator can be replaced by the sum of clockwise and counterclockwise rotating electric fields. Only the electric field rotating in the same direction as an electron interacts strongly with it. As required for cylindrical geometry, distances around the line are measured in radians.

Consider an electron beam element contained inside an element of the line that is "a" m^2 in area by $\Delta\theta$ rad long. A value n of the electron beam density (per m^2 per rad) attracts and confines an element of charge comprising $-Zean\Delta\theta$ C, liberating an equal but opposite charge to flow to the circuit elements. Obviously, the current from this beam segment is

$$i_1 = Zea\,\frac{\partial n}{\partial t}\,\Delta\theta.$$

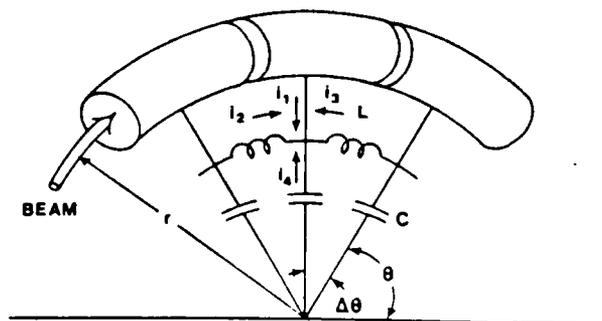The other currents in the circuit are easily represented:

FIG. 1. Geometry assumed: The inner and outer conductors providing the radial dc confining field are not shown.

$$\frac{di_2}{dt} = \frac{1}{L}(V_{(\theta - \Delta\theta)} - V_{(\theta)}),$$

$$\frac{di_3}{dt} = \frac{1}{L}(V_{(\theta + \Delta\theta)} - V_{(\theta)}),$$

$$i_4 = -C\frac{dV_{(\theta)}}{dt}.$$

If all currents are represented as derivatives, they can be added according to Kirchhoff:

$$\frac{di_1}{dt} + \frac{di_2}{dt} + \frac{di_3}{dt} + \frac{di_4}{dt} = 0,$$

or

$$Zea\frac{\partial^2 n}{\partial t^2}\Delta\theta + \frac{1}{L}(V_{(\theta - \Delta\theta)} - 2V_{(\theta)}$$

$$+ V_{(\theta + \Delta\theta)}) - C\frac{d^2 V_{(\theta)}}{dt} = 0.$$

Next, we assume that the capacitances and inductances are derived in terms of units per rad, as follows:

$$C = C_0\Delta\theta, \quad L = L_0\Delta\theta.$$

By letting $\Delta\theta \to 0$, a differential equation results:

$$Zea\frac{\partial^2 n}{\partial t^2} + \frac{1}{L_0}\frac{\partial^2 V}{\partial\theta^2} - C_0\frac{\partial^2 V}{\partial t^2} = 0. \tag{2}$$

This is the first of three equations required.

The second equation refers to the change of orbital frequency with energy. In circular motion in a logarithmic potential well, we have

$$\frac{mv^2}{r} = \frac{-ZeV_0}{r\ln(r_2/r_1)}.$$

We note that the linear velocity v is independent of the depth of the particle in the well,

$$v = \left(\frac{-ZeV_0}{m\ln(r_2/r_1)}\right)^{1/2} = v_0.$$

Also, the kinetic energy of the particle is independent of the particle depth in the well,

$$\frac{mv^2}{2} = -\frac{ZeV_0}{2\ln(r_2/r_1)}.$$

Consequently, any work extracted from the orbital motion of the particle must come from the particle's descent into the well. If E_θ is an electric field tangent to the electron orbit (V/m), we obtain

$$ZeE_\theta v_0 = -\frac{ZeV_0}{r\ln(r_2/r_1)}\frac{dr}{dt}.$$

But $\omega \simeq v_0/r$, so

$$\frac{d\omega}{dt} = -\frac{v_0}{r^2}\frac{dr}{dt}.$$

Thus we derive an equation relating the rate of change of angular frequency to an azimuthal electric field,

$$\frac{v_0 E_\theta}{V_0/\ln(r_2/r_1)}\frac{v_0}{r} = \frac{d\omega}{dt} = \frac{\partial\omega}{\partial t} + \omega\frac{\partial\omega}{\partial\theta}. \tag{3}$$

The term $d\omega/dt$ is the actual change of angular frequency of a given particle, $\partial\omega/\partial t$ is the observed change of angular frequency in a fixed region of observation, and $\omega(\partial\omega/\partial\theta)$ is a correction term to compensate for faster particles replacing slower particles in the region of observation which gives a false acceleration. This is the second of three equations needed to solve the problem.

The third equation required is simply the conservation of particles moving in a ring,

$$\frac{\partial n}{\partial t} + n\frac{\partial\omega}{\partial\theta} + \omega\frac{\partial n}{\partial\theta} = 0. \tag{4}$$

Here, $\partial n/\partial t$ is the change of electron density in the region of observation, $n(\partial\omega/\partial\theta)$ is the loss of electrons caused by electrons leaving the region at higher velocity than those entering, and $\omega(\partial n/\partial\theta)$ is the loss caused by a larger density leaving the region than entering. The reason that three equations are required is that the above three equations have three free variables, n, ω, and V. The electric field E_θ is derived from V as follows:

$$E_\theta = -\frac{1}{r}\frac{\partial V}{\partial\theta}.$$

The above three equations in n, ω, and V are linearized and reduced to algebraic expressions by the following expressions:

$$\omega = \omega_0 + \omega_1 e^{i(l\theta - \omega_2 t)},$$

$$n = n_0 + n_1 e^{i(l\theta - \omega_2 t)},$$

$$V = V_1 e^{i(l\theta - \omega_2 t)}.$$

Here, ω_0 is the original frequency, ω_1 is a parameter, ω_2 is the new orbital frequency caused by the electron ring–line interaction, and l is a harmonic number. The electron density n is composed of a large constant density n_0 and a small fluctuating density n_1. Concerning the azimuthal potential V, we assume no dc potential but only a small fluctuation V_1, as any dc potential is shorted out by the inductors.

When the above expressions are placed into our basic equations, which are then linearized, we obtain

$$Zea\omega_2^2 n_1 + l^2 V_1/L_0 - C_0\omega_2^2 V_1 = 0, \tag{5}$$

$$\omega_1\omega_2 - \omega_1 l\omega_0 = \frac{v_0^2}{V_0\ln(r_2/r_1)}\frac{lV_1}{r^2}, \tag{6}$$

$$n_2\omega_2 - n_2 l\omega_0 = n_0 l\omega_1. \tag{7}$$

Using these three equations to eliminate n_1, ω_1, and V_1, we obtain our final equation,

$$\frac{l^2}{L_0 C_0\,\omega_2^2} + \frac{Zeal^2\,\omega_0^2\,n_0}{C_0 V_0/\ln(r_2/r_1)(\omega_2 - l\omega_0)^2} = 1. \tag{8}$$

The above equation resembles that for a two-stream interaction, with one major difference—the second term is always negative.[2] If Z is negative for an electron, V_0 must be positive to confine it, and conversely. This is a consequence of the negative-mass characteristic of the system, in which an electric field that decelerates an electron increases its angular velocity.

A plot of the left-hand and right-hand sides (Fig. 2) reveals a quite different graph than that for the conventional beam–plasma interaction. Note that the possibly unstable roots lie above the harmonics of the electron orbital frequency, $l\omega_0$.

A calculation of the system gain may be made by noting

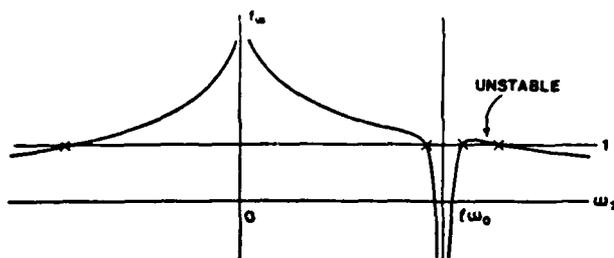1991   Phys. Fluids, Vol. 28, No. 6, June 1985

Igor Alexeff   1991

58

FIG. 2. Dispersion function for one beam. The unstable roots go complex if $f(\omega)$ is pulled below 1. The left-hand side of Eq. (8) is $f(\omega)$.

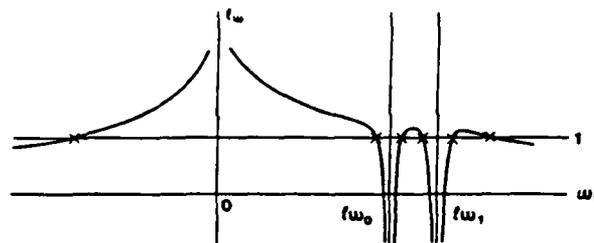FIG. 3. Dispersion function for two beams. The four right-hand roots go complex if $f(\omega)$ is pulled below 1.

that the unstable roots lie near $l\omega_0$, or

$$\Delta\omega = \omega_2 - l\omega_0, \qquad (9)$$

where $\Delta\omega$ is small compared to ω_2 and $l\omega_0$.

The fourth-order equation, Eq. (8), may be written in terms of powers of $\Delta\omega$ and studied as successive approximations, as shown below. Let

$$\frac{l^2}{L_0 C_0} = A, \quad -\frac{Zeal^2 \omega_0^2 n_0}{C_0 V_0/\ln(r_2/r_1)} = B.$$

Then our equation is

$$A/\omega_2^2 - B/(\omega_2 - l\omega_0)^2 = 1.$$

If we let $\Delta\omega = \omega_2 - l\omega_0$, then we get

$$A/(\Delta\omega + l\omega_0)^2 - B/\Delta\omega^2 = 1.$$

This equation is rationalized as follows:

$$A\Delta\omega^2 - B(\Delta\omega + l\omega_0)^2 = \Delta\omega^2(\Delta\omega + l\omega_0)^2,$$

$$A\Delta\omega^2 - B\Delta\omega^2 - 2B\Delta\omega l\omega_0 - Bl^2\omega_0^2$$

$$= \Delta\omega^4 + 2\Delta\omega^3 l\omega_0 + \Delta\omega^2 l^2 \omega_0^2,$$

$$0 = \Delta\omega^4 + 2\Delta\omega^3 l\omega_0 + \Delta\omega^2(l^2 \omega_0^2 - A + B)$$

$$+ \Delta\omega(2Bl\omega_0) + Bl^2\omega_0^2. \qquad (10)$$

As $\Delta\omega$ is small relative to ω_2 and $l\omega_0$, the higher power terms are smaller, and the equation can be solved by successive approximations, as shown below:

$$-Bl^2\omega_0^2/2Bl\omega_0 = \Delta\omega \quad \text{or} \quad -l\omega_0/2 = \Delta\omega. \qquad (11)$$

This violates our assumption [Eq. (9)] that $\Delta\omega \ll l\omega_0$, and so is not a valid solution.

Next we try the second-order case,

$$-Bl^2\omega_0^2/(l^2\omega_0^2 - A + B) = \Delta\omega^2. \qquad (12)$$

This approximation yields a small value for $\Delta\omega$ because one never gets enough beam density, so B is small. As $B \ll A$, we can drop it from the denominator to obtain

$$-Bl^2\omega_0^2/(l^2\omega_0^2 - A) = \Delta\omega^2. \qquad (13)$$

The above is complex and large if $A < l^2\omega_0^2$. Thus, maximum growth occurs when

$$A = l^2/L_0 C_0 < l^2\omega_0^2,$$

or when the electron electrostatic gyrofrequency is slightly larger than $(1/L_0 C_0)^{1/2}$. We note that the units of $1/L_0 C_0$ correspond to rad^2/sec^2, which is what is required in cylindrical geometry.

If $\Delta\omega$ becomes large, the third-order term cannot be ignored. The third-order approximation is

$$-Bl^2\omega_0^2/2l\omega_0 = \Delta\omega^3, \qquad (14)$$

or

$$\frac{Zeal^2\omega_0^2 n_0(l\omega_0)}{2C_0 V_0/\ln(r_2/r_1)} = \Delta\omega^3,$$

or

$$\left\{ \begin{array}{c} -1 \\ \frac{1}{2} \quad +i \quad \frac{\sqrt{3}}{2} \\ \frac{1}{2} \quad -i \quad \frac{\sqrt{3}}{2} \end{array} \right\} \left| \frac{Zean_0}{2C_0 V_0/\ln(r_2/r_1)} \right|^{1/3} l\omega_0 = \Delta\omega. \qquad (15)$$

The absolute value sign in Eq. (15) removes confusion caused by the quantity inside always being negative. The results correspond to one root being real and slightly below $l\omega_0$, and two being complex, and slightly above $l\omega_0$, in good agreement with Fig. 2.

The fourth-order approximation need not be considered, as Fig. 2 shows that the fourth root is so far from $l\omega_0$ that the approximation that $\Delta\omega$ is small is not valid. One can verify that these approximations are properly ordered in magnitude by substituting the above solution back into the basic equation [Eq. (10)]. One then finds that the zero-order and third-order terms are larger than the first, second, and fourth-order terms. There are no higher-order terms.

III. THEORY FOR AN ELECTRON SPREAD IN RADIUS (VLASOV THEORY)

We next extend the formalism to a distribution in radius of the electrons. As an insight into the process, let us consider two electron rings closely spaced in radius and of equal density. The orbit frequencies are $l\omega_0$ and $l\omega_1$. A graph of the dispersion function is shown in Fig. 3. We find two sets of unstable roots. One set lies above $l\omega_0$ and $l\omega_1$ (above the distribution function) and corresponds to a pair of roots depending on the total density of the two beams. The second pair lies between the two beams and corresponds to waves occurring inside the distribution function.

We can proceed to a continuous distribution function by the superposition of many beams. We rewrite the dispersion function as follows. Let

$$A = \frac{l^2}{L_0 C_0}, \quad D = -\frac{Zeal^2}{C_0 V_0/\ln(r_2/r_1)},$$

so

1992   Phys. Fluids, Vol. 28, No. 6, June 1985   Igor Alexeff   1992

59

$A/\omega_2^2 - D\omega_0^2 n_0/(\omega_2 - l\omega_0)^2 = 1.$

Let the density of a given beam be written as

$$n_0 = N_0 f(\omega_0)\Delta\omega_0. \tag{16}$$

A superposition of many beams leads to the integral below:

$$\frac{A}{\omega_2^2} - DN_0 \int \frac{[(\omega_2 - \Delta\omega)^2/l]^2 f[(\omega_2 - \Delta\omega)/l](-d\Delta\omega/l)}{(\Delta\omega)^2} = 1.$$

The above integral may be evaluated by expansion in a Taylor series:

$$f\left(\frac{\omega_2 - \Delta\omega}{l}\right) = f\left(\frac{\omega_2}{l}\right) + \frac{\partial f(\omega_2/l)}{\partial\omega}\left(-\frac{\Delta\omega}{l}\right) + \cdots. \tag{18}$$

The constant term in Eq. (18) is nonzero. The integral containing it does not diverge to infinity because $\Delta\omega$ is complex and does not go to zero for integration along the axis. This term yields the roots corresponding to the pair lying above $l\omega_0$ and $l\omega_1$ in Fig. 3.

The first derivative term in Eq. (18) corresponds to the solution of Vlasov as modified by Landau.[3] Because of causality, one assumes no infinite solution at $t = -\infty$. This means that the root is assumed to be above the x axis.[4] Following Landau, one goes halfway around the pole, as shown in Fig. 4. The result is as follows:

$$\int \frac{[(\omega_2 - \Delta\omega)/l]^2 f'[(\omega_2 - \Delta\omega)/l](-\Delta\omega/l)(-d\Delta\omega/l)}{(\Delta\omega)^2}$$

$$= +\left(\frac{\omega_2}{l}\right)^2 f'\left(\frac{\omega_2}{l}\right)\left(\frac{\pi i}{l^2}\right), \quad f' = \frac{\partial f}{\partial\omega}. \tag{19}$$

We assume that the main part of the real dispersion function comes from the resonator. This occurs because $A \gg DN_0\omega_0^2$, since the beam density N_0 is always small. We obtain

$$\frac{A}{\omega_2^2} - DN_0\left(\frac{\omega_2}{l}\right)^2 f'\left(\frac{\omega_2}{l}\right)\left(\frac{\pi i}{l^2}\right) = 1.$$

This can be rewritten as follows:

$$\frac{A}{\omega_2^2} = 1 + DN_0\left(\frac{\omega_2}{l}\right)^2 f'\left(\frac{\omega_2}{l}\right)\left(\frac{\pi i}{l^2}\right).$$

As the complex term can be considered small, we replace ω_2 by $l\omega_0$, to get

$$\frac{A}{\omega_2^2} = 1 + DN_0\omega_0^2 f'\left(\frac{\omega_2}{l}\right)\frac{\pi i}{l^2},$$

This can be rewritten as shown:

$$\frac{A}{1 + DN_0\omega_0^2 f'(\omega_2/l)(\pi i/l^2)} = \omega_2^2.$$

We leave f' in terms of ω_2/l to emphasize that the distribu-
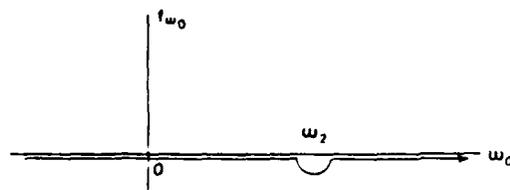
FIG. 4. Integration path used.

tion function can interact with harmonics of the electron orbit frequency.

We expand the right-and left-hand sides, keeping only the first two terms of each:

$$\frac{A}{\omega_2^2} - DN_0 \int \frac{\omega_0^2 f(\omega_0)d\omega_0}{(\omega_2 - l\omega_0)^2} = 1. \tag{17}$$

Let $\omega_2 - l\omega_0 = \Delta\omega$ and one obtains

$$A[1 - DN_0 \omega_0^2 f'(\omega_2/l)(\pi i/l^2) + \cdots]$$
$$= \omega_r^2 + 2i\omega_r\omega_i + \cdots.$$

Next, equate real and imaginary parts:

$$A = \omega_r^2 \quad \text{or} \quad \pm\frac{l}{\sqrt{L_0 C_0}} = \omega_r,$$

$$-ADN_0 \omega_0^2 f'\left(\frac{\omega_2}{l}\right)\frac{\pi}{l^2} = 2\omega_r\omega_i,$$

or

$$\omega_r^2\left(\frac{Zeal^2}{C_0 V_0/\ln(r_2/r_1)}\right) N_0 \omega_0^2 f'\left(\frac{\omega_2}{l}\right)\frac{\pi i}{l^2} = 2\omega_r\omega_i,$$

or, since $\omega_r \approx \omega_2 \approx l\omega_0$,

$$\pi i\frac{\omega_0}{2}\left(\frac{Zeal \omega_0^2 N_0}{C_0 V_0/\ln(r_2/r_1)}\right)\frac{\partial f}{\partial\omega}\left(\frac{\omega_2}{l}\right) = \omega_i. \tag{20}$$

The quantity in parentheses is always negative, as a negative Z requires V_0 be positive for electron confinement. Consequently, if $\partial f/\partial\omega$ is positive at (ω_2/l), ω_i is negative, and the wave damps. This is understandable in an energy model, as the deeper an electron lies in the potential well, the higher its frequency, i.e., the lowest-energy states have the highest frequency.

IV. SATURATION OF GROWTH AND PHYSICAL LIMITS TO HARMONIC EMISSION

The saturation of the growth for the various l modes is of interest, because it gives some insight as to the relative power output at the various harmonics. For the ring model, this is done by noting that as work is extracted from the electrons, they drift inward, change their frequency of rotation, and move away from the resonance condition which yields high gain. A change of gain of a factor of 2 is considered as having moved "off resonance." Such a treatment has been used in the study of the saturation of an electron beam-plasma interaction[5] and the study of the calutron isotope separator.[6]

To compute the frequency shift, we insert a $\Delta\omega$ of half the value of that given by Eq. (15) into Eq. (13), and solve for the frequency shift as shown below:

$$\left(-\frac{Zeal \omega_0^2 n_0}{C_0 V_0/\ln(r_2/r_1)}\right)\frac{l^2 \omega_0^2}{l^2 \omega_0^2 - l^2/L_0 C_0}$$

$$= \left(\frac{1}{2}\left|\frac{Zean_0}{2C_0 V_0/\ln(r_2/r_1)}\right|^{1/3} l\omega_0\right)^2. \tag{21}$$

1993   Phys. Fluids, Vol. 28, No. 6, June 1985   Igor Alexeff   1993

60

Since we are no longer at resonance, the cubic term may be neglected, as may be shown by inserting $\Delta\omega/2$ back into Eq. (10).

A little algebra reveals the following result:

$$-2^{8/3}\left|\frac{Zean_0}{C_0V_0\ln(r_2/r_1)}\right|^{1/3}\omega_0^2 = \omega_0^2 - \frac{1}{L_0C_0} \simeq 2\omega_0\delta\omega.$$

(22)

Thus, the frequency shift for detuning is the same for *all* harmonics. Since all harmonics saturate at the same level, we would expect the faster growing, higher-frequency harmoncis to preferentially radiate the power.

The gain of the system can be controlled by changing the impedance z of the line. As $z = (L_0/C_0)^{1/2}$, and $\omega_0 = (1/L_0C_0)^{1/2}$, we find that $z\omega_0 = 1/C_0$. Factoring $C_0^{-1/3}$ from Eq. (15), we can rewrite it as shown below to demonstrate the change of gain with z:

$$\left\{\begin{array}{c} -1 \\ \dfrac{1}{2} + i\ \dfrac{\sqrt{3}}{2} \\ \dfrac{1}{2} - i\ \dfrac{\sqrt{3}}{2} \end{array}\right\} \left|\frac{Zean_0}{2V_0/\ln(r_2/r_1)}\right|^{1/3} l\omega_0^{4/3}z^{1/3} = \Delta\omega.$$

(23)

Thus, by proper line (or cavity) design, the gain may be increased while the frequency ω_0 is kept constant.

In the ring model, growth is reduced when the wavelength on the beam becomes comparable to the diameter of the line, $\sqrt{a}$, and electric fields from a charge clump extend directly to the next clump without intersecting the line. Thus, there is a geometrical high-frequency limit comparable to that found in traveling wave tubes. However, an instability in the bare electron ring now appears although it grows more slowly.[7]

For the Vlasov case, the problem appears to be similar to that involving Landau damping, and one would expect the velocity distribution function to develop a plateau in beam angular velocity ω in the neighborhood of $\omega_0 = 1/(L_0C_0)^{1/2}$. As in the case of Landau damping, one expects the width of the plateau to depend on the amplitude of the wave.[8] Thus, we suspect that a rapidly growing wave might create a large plateau and absorb energy from a large fraction of the orbiting electrons. We will attempt this more detailed calculation in the near future.

V. CONCLUSIONS AND GENERAL OBSERVATIONS

In conclusion, we find that monotonically increasing (Maxwellian-like) distribution function with increasing orbital frequency is stable to wave growth in our maser. A monotonically decreasing, inverted energy distribution function is unstable. Also, for beam-like cases, the unstable roots occur above harmonics of the electron orbital frequency.

Note that in this device, the energy distribution is always inverted, as the central wire occupies the position required by the lowest energy states. For both beam-like and distributed $F(\omega)$ cases, the growth rate of a harmonic increases linearly as the harmonic number, until the basic assumptions become invalid. Both the above conclusions sug-
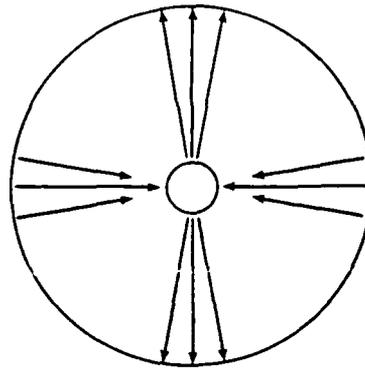
FIG. 5. Electric field lines for possible mode in coaxial waveguide. Here $l = 2$.

gest that the maser should be an effective high-frequency device, as maser action occurs in the inverted population region (the high-field, high-frequency region near the wire), and growth tends to occur at the harmonics of the orbital frequency.

Note added in proof: As of April 1985, the operating frequency has been extended to 1 THz (10^{12} Hz).

APPENDIX: EXISTENCE OF COAXIAL CAVITY MODES

The case of growth at the harmonics of the electron electrostatic gyrofrequency is of interest in our maser. We require rotating sectors of opposite electric field in the interaction region. Such sectors do not occur in ordinary cavity resonators, but they do occur in our maser because of the presence of the central wire. They are referred to as coaxial modes,[9] as shown in Fig. 5.

[1] I. Alexeff and F. Dyer, Phys. Rev. Lett. **45**, 351 (1980); I. Alexeff and F. Dyer, *Proceedings 1983 International Conference on Infrared and Millimeter Waves*, (IEEE, New York, 1983), p. F2.4; I. Alexeff and F. Dyer, *Proceedings 1984 International Conference on Plasma Physics*, edited by M. Q. Tran (Ecole Polytechnique Federal de Lausanne, Lausanne, Switzerland, 1984); p. 394; I. Alexeff and F. Dyer, Laser Focus **20**(12), 36 (1984); **16**(12), 28 (1980).

[2] For a related relativistic treatment in an electron shell, see Y. Y. Lau and D. Chernin, Phys. Rev. Lett. **52**, 1425 (1984); D. Chernin and Y. Y. Lau, Phys. Fluids **27**, 2319 (1984).

[3] L. Landau, J. Phys. U. S. S. R. **10**, 25 (1946). The detailed structure around the Landau pole is discussed in I. Alexeff and Osamu Ishihara, IEEE Trans. Plasma Sci. PS-6, 212 (1978).

[4] The author acknowledges a discussion with Akira Hasegawa of AT&T Bell Labs on this point.

[5] V. D. Shapiro, Sov. Phys. JETP **17**, 416 (1963).

[6] I. Alexeff, IEEE Trans. Plasma Sci. PS-6, 539 (1978).

[7] I. Alexeff, IEEE Trans. Plasma Sci. PS-12, 280 (1984).

[8] N. A. Krall and A. W. Trivelpiece, *Principles of Plasma Physics* (McGraw-Hill, New York, 1973), p. 531.

[9] H. R. Skilling, *Fundamentals of Electric Waves* (Wiley, New York, 1948), p. 218; N. Marcuvitz, *MIT Waveguide Handbook*, Radiation Lab Series No. 10 (Boston Technical Publishers, Lexington, MA, 1964), p. 72.

1994   Phys. Fluids, Vol. 28, No. 6, June 1985   Igor Alexeff   1994

61

Growth of Harmonic Perturbations of an Electron Shell Orbiting a Positively-Charged Wire (Orbitron)

IGOR ALEXEFF, FELLOW, IEEE

Abstract—The negative-mass instability of a cylindrical shell of electrons orbiting a positively-charged wire was studied. The harmonics of the orbital frequency are found to grow faster than the fundamental, with a growth constant proportional to the square root of the harmonic number.

INTRODUCTION

THE NEGATIVE-MASS instability of electrons orbiting a positively-charged wire has been used to produce millimeter and submillimeter microwave radiation in the Orbitron [1]. This instability is the most rapidly growing of all those having a radial electric field and an axial magnetic field [2]. This work suggests why the Orbitron vacuum gauge [3] discharge extinguishes at high vacuum [4], while the Penning discharges does not. According to [2], the Orbitron electron ring is unstable, while the Penning discharge ring is not.

In this paper, we expand the work of [2] to investigate the harmonics of the orbit frequency. In the absence of a cavity

resonator, we find that the harmonics of the orbit frequency are more unstable than the fundamental, with growth constants proportional to the square root of the harmonic number.

TEXT

Consider a circular shell of electrons of radius r, orbiting a positive wire. The electron shell thickness is Δr. As shown in Fig. 1, the electric field due to a rod of charge at θ' on an electron at θ is given as

$$\Delta E_\theta = -\frac{Zen\,\Delta r\Delta\theta}{2\pi\epsilon_0 D}\cos\left(\frac{\theta'-\theta}{2}\right). \tag{1}$$

Here ΔE_θ is the tangental electric field (volts/meter), Z is the electron charge on an electron (-1), e is the magnitude of the charge (1.60×10^{-19} C), n is the density of electrons per square meter per radian, Δr is the thickness of the shell (meters). $\Delta\theta$ is the width of the charged rod (radians), ϵ_0 is the permittivity of vacuum (farads per meter), D is the distance from the center of the rod to the test electron (meters), and

$$\cos\left(\frac{\theta'-\theta}{2}\right)$$

is a compensation for the fact that only an electric field paral-
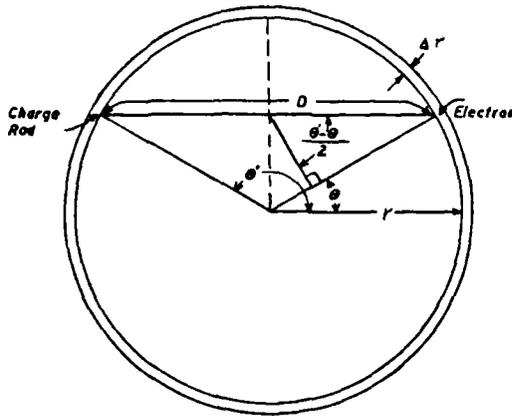
Fig. 1. Geometry used in computing internal forces in electron shell.

lel to the direction of motion E_θ provides any long-term acceleration.

But

$$D = 2r \sin\left(\frac{\theta' - \theta}{2}\right)$$

so

$$\Delta E_\theta = -\frac{Zen\,\Delta r \Delta\theta \cos\left(\frac{\theta' - \theta}{2}\right)}{2\pi\epsilon_0 2r \sin\left(\frac{\theta' - \theta}{2}\right)}. \tag{2}$$

We next note that by symmetry the charge of the cylindrical shell cannot accelerate a given electron. We therefore consider n_1 a perturbation in density of a shell of density n_0. We also assume that this perturbation is a harmonic l of the rotational wavenumber. We then integrate over the shell to find the electric field E_θ at the test electron which is produced by the perturbation.

Let $n_1 = n_2 e^{i(l\theta - \omega t)}$, where l is a positive integer:

$$E_0 = -\frac{Zen_2\Delta r}{4\pi\epsilon_0 r} \int_0^{2\pi} \frac{\cos\left(\frac{\theta' - \theta}{2}\right) e^{i(l\theta' - \omega t)}}{\sin\left(\frac{\theta' - \theta}{2}\right)} d\theta' \tag{3}$$

$$= -\frac{Zen_2\Delta r}{4\pi\epsilon_0 r} \int_0^{2\pi} \frac{\cos\left(\frac{\theta' - \theta}{2}\right) e^{i(l\theta' - l\theta)} e^{i(l\theta - \omega t)} d\theta'}{\sin\left(\frac{\theta' - \theta}{2}\right)} \tag{4}$$

$$= -\frac{Zen_2\Delta r}{4\pi\epsilon_0 r} e^{i(l\theta - \omega t)} \int_0^{2\pi} \frac{\cos\left(\frac{\theta' - \theta}{2}\right)}{\sin\left(\frac{\theta' - \theta}{2}\right)} e^{i(l\theta' - l\theta)} d\theta'. \tag{5}$$

Note that the singularity in the integral at $\theta' - \theta = 0$ does not really exist, as when the distance D becomes comparable to Δr, finite-geometry effects keep the electric field from diverging to infinity.

We now use complex notation

$$\int_0^{2\pi} \frac{\cos\left(\frac{\theta' - \theta}{2}\right)}{\sin\left(\frac{\theta' - \theta}{2}\right)} e^{i(l\theta' - l\theta)} d\theta' \tag{6}$$

$$= i \int_0^{2\pi} \frac{\exp\left[i\left(\frac{\theta' - \theta}{2}\right)\right] + \exp\left[-i\left(\frac{\theta' - \theta}{2}\right)\right]}{\left(\exp\left[i\left(\frac{\theta' - \theta}{2}\right)\right] - \exp\left[-i\left(\frac{\theta' - \theta}{2}\right)\right]\right)} e^{i(l\theta' - l\theta)} d\theta' \tag{7}$$

$$= i \int_0^{2\pi} \frac{\exp\left[i\left(l\theta' - l\theta + \frac{\theta' - \theta}{2}\right)\right] + \exp\left[i\left(l\theta' - l\theta - \frac{\theta' - \theta}{2}\right)\right]}{\exp\left[i\left(\frac{\theta' - \theta}{2}\right)\right] - \exp\left[-i\left(\frac{\theta' - \theta}{2}\right)\right]} d\theta'. \tag{8}$$

Let

$$\frac{\theta' - \theta}{2} = \Phi, \quad d\theta' = 2d\Phi, \quad (l\theta' - l\theta) = 2l\Phi,$$

$$= i \int_0^\pi \frac{e^{i(2l+1)\Phi} + e^{i(2l-1)\Phi}}{e^{i\Phi} - e^{-i\Phi}} 2d\Phi. \tag{9}$$

The above integral has been evaluated in two different ways. In the form of (5), it was evaluated on a computer. In the form of (9), it was evaluated as a contour integral, using the contour shown in Fig. 2. Both approaches yield the result shown in (10)

$$2i \int_0^\pi \frac{e^{i(2l+1)\Phi} + e^{i(2l-1)\Phi}}{e^{i\Phi} - e^{-i\Phi}} d\Phi = 2\pi i. \tag{10}$$
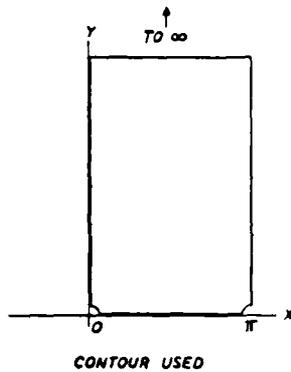
CONTOUR USED

Fig. 2. Contour used in evaluating integral of (9).

Thus we find that

$$E_0 = - \frac{Zen_2 \Delta r}{4\pi\epsilon_0 r} e^{i(l\theta - \omega t)} 2\pi i \tag{11}$$

or

$$E_0 = - i \frac{Zen_2 \Delta r}{2\epsilon_0 r} e^{i(l\theta - \omega t)}. \tag{12}$$

This is the first equation of three needed to solve the problem.

Next, we consider the problem of the shift in frequency with energy loss. We know that centrifugal force balances the electric field

$$\frac{mv^2}{r} = - \frac{ZeV_0}{r \ln(r_2/r_1)}.$$

Here m is the mass of an electron (kilogram), v is the tangential velocity (meter/second), V_0 is the positive potential applied to the wire (volts), and r_2 and r_1 are the radius of an outer cylindrical container, and of the wire, respectively. We now note that

$$\frac{mv^2}{2} = - \frac{ZeV_0}{2\ln(r_2/r_1)} \qquad v_0 = \sqrt{- \frac{ZeV_0}{m\ln(r_2/r_1)}}$$

or the kinetic energy and linear velocity are constants for circular motion in a logarithmic potential well. This simplifies our calculation, as any energy W removed from the orbital motion must come only from the electron's descending into the potential well! In other words,

$$Zev_0 E_\theta = \frac{dW}{dt} = - \frac{ZeV_0}{r \ln(r_2/r_1)} \frac{dr}{dt}.$$

But

$$\omega = \frac{v_0}{r}$$

so

$$\frac{d\omega}{dt} = - \frac{v_0}{r^2} \frac{dr}{dt}.$$

So

$$\frac{Zev_0 E_0}{ZeV_0/\ln(r_2/r_1)} \frac{v_0}{r} = \frac{d\omega}{dt}.$$

If E_θ is positive (retarding electrons), then

$$\frac{d\omega}{dt}$$

is p ... (frequency increases). Thus removing energy from an el   on increases its angular velocity, a situation referred to as a form of negative-mass instability. This name comes from an analog to a linear beam of particles. In this case, a decrease of energy would result in an increase of linear velocity if the particles possessed negative mass. Note that v_0 is a constant, a consequence of kinetic energy conservation. Finally, we obtain

$$\frac{\omega_0^2 E_\theta r}{V_0/\ln(r_2/r_1)} = \frac{d\omega}{dt} \tag{13}$$

or

$$\frac{\partial\omega}{\partial t} + \omega \frac{\partial\omega}{\partial\theta} = \frac{\omega_0^2 r E_\theta}{V_0/\ln(r_2/r_1)}. \tag{14}$$

This is the second equation needed.

Finally, we have conservation of particles in a cylindrical system,

$$\frac{\partial n}{\partial t} + n \frac{\partial\omega}{\partial\theta} + \omega \frac{\partial n}{\partial\theta} = 0. \tag{15}$$

Let

$$E_\theta = E_1 e^{i(l\theta - \omega_2 t)} \tag{16}$$

$$n = n_0 + n_2 e^{i(l\theta - \omega_2 t)} \tag{17}$$

$$\omega = \omega_0 + \omega_1 e^{i(l\theta - \omega_2 t)}. \tag{18}$$

Using the above expressions for E_θ, n, and ω in our three basic equations and linearizing them, we reduce the differential equations to the three following algebraic expressions:

$$E_1 = - i \frac{Zen_2 \Delta r}{2\epsilon_0 r} \tag{19}$$

$$- i\omega_1\omega_2 + \omega_0\omega_1 il = \frac{\omega_0^2 r E_1}{V_0/\ln(r_2/r_1)} \tag{20}$$

$$- i\omega_2 n_2 + n_0\omega_1 il + \omega_0 n_2 il = 0. \tag{21}$$

These can be solved as follows:

$$n_2 = \frac{n_0\omega_1 l}{\omega_2 - l\omega_0} \tag{22}$$

$$\omega_1 = \frac{i\omega_0^2 r E_1}{(\omega_2 - l\omega_0) V_0/\ln(r_2/r_1)} \tag{23}$$

or

$$n_2 = i \frac{n_0 l\omega_0^2 r E_1}{(\omega_2 - l\omega_0)^2} \tag{24}$$

$$E_1 = - i(i) \frac{n_0 l\omega_0^2 r}{(\omega_2 - l\omega_0)^2} \frac{Ze\Delta r E_1}{2\epsilon_0 r V_0/\ln(r_2/r_1)} \tag{25}$$

$$1 = \frac{n_0 l\omega_0^2}{(\omega_2 - l\omega_0)^2} \frac{Ze\Delta r}{2\epsilon_0} \frac{1}{V_0/\ln(r_2/r_1)}. \tag{26}$$

Our final result is

$$\omega_2 - l\omega_0 = \sqrt{\frac{n_0 lZe\Delta r}{2\epsilon_0 V_0 / ln(r_2/r_1)}} \; \omega_0. \tag{27}$$

The instability occurs because for electrons, Z is negative, while V_0 is positive. If positive particles were in orbit, both Z and V_0 would reverse signs.

CONCLUSION

In conclusion, we find that a circular shell of electrons orbiting a positively-charged wire is unstable, and that the instability grows as the square root of the harmonic number. Thus the second harmonic grows $\sqrt{2}$ faster than the fundamental, the third harmonic grows as $\sqrt{3}$ faster than the fundamental, etc. The equation eventually becomes invalid for very high harmonics, when the wavelength, for example, becomes comparable to the shell thickness Δr. Note that going to $-l$ formally turns off the instability. This conclusion is invalid, as the integration procedure used in deriving (10) then must be modified.

Reference [1] has demonstrated that the instability of electrons orbiting a positive wire can generate millimeter micro-waves, and [2] has demonstrated that this instability is most unstable if no magnetic field is present parallel to the wire. Here we note that the higher harmonics are even more unstable than the fundamental orbit frequency, subject to the limitation of the special case of circular orbits. We therefore suspect that the device of [1] (Orbitron) can generate even higher frequency microwaves by operating at harmonics of the electron gyrofrequency.

REFERENCES

[1] I. Alexeff and F. Dyer, *Phys. Rev. Lett.*, vol. 45, p. 351, 1980.
[2] Y. Y. Lau and D. Chernin, *Phys. Rev. Lett.*, vol. 52, p. 1425, 1984.
[3] R. H. Hooverman, *J. Appl. Phys.*, vol. 34, p. 3035, 1963. W. G. Mourad, F. Pauly, and R. G. Herb, *Rev. Sci. Instrum.*, vol. 35, p. 661, 1964.
[4] R. G. Herb, private communication.
[5] Y. Y. Lau and D. Chernin, *Phys. Fluids*, vol. 9, p. 2319, 1984.

ORBITRON OPERATION AT 1 THz

Igor Alexeff, Fred Dyer, and Wlodek Nakonieczny

Electrical Engineering Department
The University of Tennessee
Knoxville, TN 37996-2100

We have extended the operating frequency of our Orbitron[1] maser up to 1 THz (10^{12} Hz, or $\lambda = 1/3$ mm). These advances were made by going to a thinner central wire 0.7 mils or 1.7×10^{-5} meters in diameter. Previous attempts to operate with such a fine wire failed due to mechanical breakage of the wire but advances in tube design now permit easy fabrication and reliable operation.

The basic Orbitron concept is that electrons from a glow-discharge are placed in orbit around the central, positively-charged wire. The electron orbits are negative-mass un-stable, couple to the radiation field of an external cavity, and emit stimulated microwave radiation. No external magnetic field is required. The original maser design is shown in Figure 1.
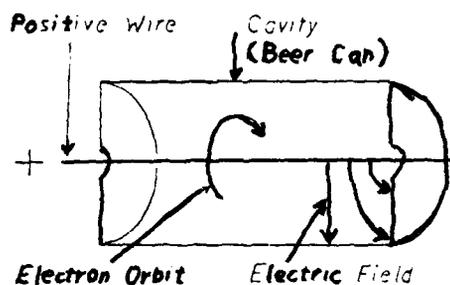
Figure 1. Original Maser Design

481

An MHD Model for the Earth's Magnetic Field with Spatially Dependent Electrical Conductivity

IGOR ALEXEFF, FELLOW, IEEE, AND J. REECE ROTH, FELLOW, IEEE

Abstract—A simple model demonstrates that symmetrical fluid flow in the earth's core can maintain a steady-state magnetic field if the electrical conductivity is allowed to vary as a function of radius (temperature).

THIS paper was inspired by an invited talk on geomagnetic fields by Dr. Radler of the German Democratic Republic at the Autumn Plasma School in the Georgian Soviet Socialist Republic in 1984. He very clearly pointed out the complexities of present MHD models [1], and we came to suspect that some simplifying assumption was missing. Conventional dc generators contain an item missing in these MHD models—a set of brushes. A similar mechanism—a change of electrical conductivity as a function of position during the cyclical flow pattern—is not present in these models.

An example of such a flow pattern is given in Fig. 1. Fluid descending at the equator of a planet's flow pattern carries magnetic field lines toward the core, opposing the outward diffusion of the field lines due to finite conductivity. In the core, the fluid flow is along the field lines to the magnetic axis, so no MHD effect is invoked. However (the new point), the flow from the magnetic axis back to the magnetic equator occurs near the surface. This flow takes place at a lower temperature and consequently at a lower conductivity than that of the descending fluid. Thus any tendency of the flow near the surface to carry field lines of the opposite polarity back into the descending fluid is greatly reduced.

To a first approximation, the fluid flow in the geomagnetic equator appears as a continually in-flowing disc, with a source at the outer edge, and a sink at the center as shown in Fig. 2. A one-dimensional slab model can be used as a first approximation to the equatorial disc, shown in Fig. 3. Here the slab is infinite in the x direction. The fluid appears at a finite radius y_0 (the equatorial radius), and disappears at $y = 0$ (the magnetic axis). The magnetic field points in the z direction. Of course, the fluid cannot physically appear and disappear, since $\nabla \cdot \vec{v} = 0$, but a conducting fluid can electrically appear and disappear as
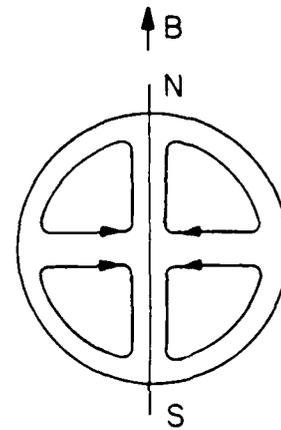
Fig. 1. Flow pattern in earth's core.
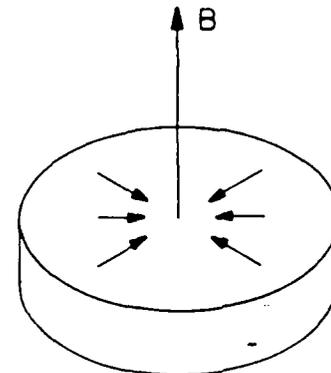
Fig. 2. Simplified flow pattern.
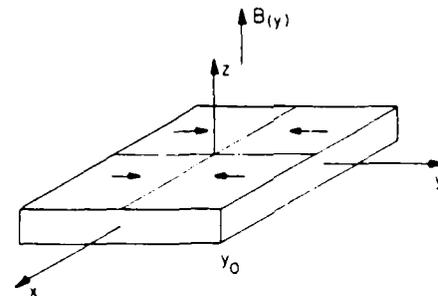
Fig. 3. Slab model

the conductivity is turned on and off, analogous to the action of a commutator. Note that the conductivity does not need to go to zero. The differential conductivity is what really matters. A model of this process can be made

by using flowing mercury. The conductivity disappears when the fluid flows into parallel insulated channels. If the fluid conductivity were to decrease with increasing temperature, the same model would hold, but the flow pattern would be reversed. The critical point is that the fluid have a change in conductivity at a fixed point in space.

Mathematically, we proceed from the MHD equations:

$$\nabla \times \vec{B} = \mu_0 \vec{j}$$

$$\vec{j} = \sigma(\vec{E} + \vec{v} \times \vec{B})$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\nabla \times (\nabla \times \vec{B}) = \nabla(\nabla \cdot \vec{B}) - \nabla^2 \vec{B} = \mu_0 \nabla \times \vec{j}$$

$$= \mu_0 \sigma(\nabla \times \vec{E} + \nabla \times (\vec{v} \times \vec{B}))$$

$$= \mu_0 \sigma\left(-\frac{\partial \vec{B}}{\partial t} + \nabla \times (\vec{v} \times \vec{B})\right).$$

As $\nabla \cdot \vec{B} = 0$, our final result is

$$\nabla^2 \vec{B} = \mu_0 \sigma\left(\frac{\partial \vec{B}}{\partial t} - \nabla \times (\vec{v} \times \vec{B})\right).$$

Expanding the third term, we find

$$\frac{1}{\mu_0 \sigma} \nabla^2 \vec{B} = \frac{\partial \vec{B}}{\partial t} - (\vec{v}(\nabla \cdot \vec{B})$$

$$- \vec{B}(\nabla \cdot \vec{v}) + (\vec{B} \cdot \nabla)\vec{v} - (\vec{v} \cdot \nabla)\vec{B}).$$

In a system with no flow and finite size, we find that $\nabla^2 \vec{B}$ must be negative. Therefore $\partial \vec{B}/\partial t$ is negative, and the magnetic field decays. However, we shall now demonstrate that the $\vec{B}(\nabla \cdot \vec{v})$ term balances this loss process.

Let us examine the other terms. Obviously, the term $\vec{v}(\nabla \cdot \vec{B}) = 0$. Two other terms are obtained by the details of our model. We assume that

$$\vec{B} = \vec{k} B(y)$$

$$\vec{v} = -\vec{j} v_0 \operatorname{sgn} y \quad \text{for} \quad |y| < y_0$$

$$= 0 \qquad \text{for} \quad |y| > y_0.$$

We obtain

$$\frac{1}{\mu_0 \sigma} \nabla^2 \vec{B}_z = \frac{\partial \vec{B}_z}{\partial t} + \vec{B}_z\left(\frac{\partial}{\partial y}\vec{v}\right) - B_z \frac{\partial}{\partial z}\vec{v} + v_0 \frac{\partial B_z}{\partial y}.$$

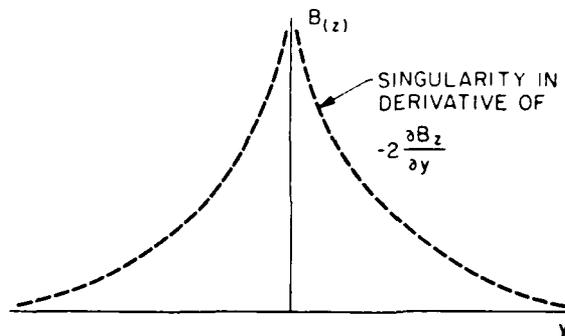The term $-v_0(\partial B_z/\partial y)$ is due to flux being carried along

Fig. 4. Plot of magnetic field as a function of radius.

by a conducting fluid, as found by Alfvén. We obtain

$$\frac{1}{\mu_0 \sigma} \frac{\partial^2 B_z}{\partial y^2} = \frac{\partial B_z}{\partial t} + B_z(-v_0(2\delta(y))) - v_0 \operatorname{sgn}(y) \frac{\partial B_z}{\partial y}$$

$$\frac{1}{\mu_0 \sigma} \frac{\partial^2 B_z}{\partial y^2} + 2v_0 B_z \delta(y)$$

$$+ v_0 \frac{\partial B_z}{\partial y} \operatorname{sgn}(y) = \frac{\partial B_z}{\partial t}.$$

Assume $\partial B_z/\partial t = 0$:

$$\frac{1}{\mu_0 \sigma} \frac{\partial^2 B_z}{\partial y^2} + 2v_0 B_z \delta(y) + v_0 \frac{\partial B_z}{\partial y} \operatorname{sgn}(y) = 0.$$

Assume symmetry about $y = 0$:

$$\frac{1}{\mu_0 \sigma} \frac{\partial^2 B_z}{\partial y^2} + v_0 B_z \delta(y) + v_0 \frac{\partial B_z}{\partial y} = 0, \quad 0 \le y \le y_0.$$

Except for the end points, the differential equation is easy to solve. Let $B(z) = B_0 e^{\gamma y}$. We obtain

$$\frac{1}{\mu_0 \sigma} \gamma^2 + v_0 \gamma = 0.$$

The values for γ are

$$\gamma = 0$$

$$\gamma = -v_0 \mu_0 \sigma.$$

Thus there are two independent solutions:

$$B(z) = B_0 e^{-v_0 \mu_0 \sigma y} + B_1.$$

The term B_0 shows the magnetic flux compressed along the axis due to the in-flowing conducting fluid, while the term B_1 can be used to fix the boundary condition.

The effect of the $\delta(y)$ function at the origin is easily seen. If we match the flows from $+y$ and $-y$, there is a singularity in the derivative at the origin, as shown in Fig. 4. The $\delta(y)$ function absorbs this singularity, by causing a rapid change in the second derivative at the origin. If we integrate the equation across the singularity, we obtain

$$\frac{\partial B_z}{\partial y_2} - \frac{\partial B_z}{\partial y_1} = -2 B_z v_0 \mu_0 \sigma.$$

Actually, what is occurring is that the inward convected flux from one side impinges on the incoming flux from the other side. In actual practice, there is a neutral-flow region between the two incoming streams where the flux accumulates.

As was quite properly pointed out by a reviewer, the case in which $(1/\mu_0\sigma)\gamma^2 + v_0\gamma = 0$ is a singular point. In general, this quantity initially is either greater than or less than zero. We can discuss this more general solution by assuming that $B(z) = B_0 e^{\gamma y + \alpha t}$. In this case, our eigenvalue equation becomes $(1/\mu_0\sigma)\gamma^2 + v_0\gamma = +\alpha$. If v_0 is sufficiently small, then α is negative, and the solution decays away in time. On the other hand, if v_0 is sufficiently large, then α is positive, and the solution grows. Exponential growth will be limited by a nonlinear term in the differential equation. Specifically, when the gradient of the magnetic pressure $B^2/2\mu_0$ approaches the gradient of the thermal pressure that drives the velocity of the magma v_0, then this velocity will decrease, and the magnetic field growth will saturate. In this case, the problem has become a more complex nonlinear one. However, we can state that the equation $(1/\mu_0\sigma)\gamma^2 v_{0\gamma} = 0$ forms the boundary between decaying solutions and growing solutions that lead to stable but nonlinear states.

If v_0 is assumed to be the flow value *resulting* from the balance of magnetic and thermal pressure, then our original equation is correct. This is what we had initially assumed but neglected to state.

Let us now estimate the value of the quantity for the e-folding distance of the current layer $1/v_0\sigma\mu_0$ in the interior of the earth. The value for μ_0 in the hot magma is obviously 1.26×10^{-6} H/m. The conductivity σ is estimated to be 3×10^5 mho/m [2]. The velocity in the core is estimated to be 4×10^{-4} m/s [3]. This velocity corresponds to our one good probe of core motion—the observed westward drift of the magnetic poles—and not the much slower velocity of the crustal plates (cm per year). Thus $y = (4 \times 10^{-4} \times 3 \times 10^5 \times 1.26 \times 10^{-6})^{-1} = 6613$ m, or 6 km, or about 10^{-3} of the earth's radius (6366 km). Thus these quantities suggest a highly compressed magnetic field near the earth's core!

Conclusions

We have derived a quite simple model for a steady-state magnetic field for the earth and for other astronomical objects as well. We have not treated the problems of the origin of the field or of its reversals over geologic time. In addition to the dynamo theories of others, let us propose the concept of flux trapping. If the earth were to pass through a weak magnetic field in space, the fluid becoming conducting at the surface would trap this flux and concentrate it in the core. This would provide the planet with an original field. We also note that the present internal field shows up as a reversed surface field. This also could be trapped and convected inward, providing periodic field reversals.

References

[1] F. Krause and K. H. Radler. *Mean-Field Magnetohydrodynamics and Dynamo Theory*. London. England: Pergamon. 1980.
[2] H. K. Moffat. *Magnetic Field Generators in Electrically Conducting Fluids*. New York: Cambridge. 1978. p. 88.
[3] H. K. Moffat. *Magnetic Field Generators in Electrically Conducting Fluids*. New York: Cambridge. 1978. p. 89.

Abstract Submitted
For the Twenty-Sixth Annual Meeting
Division of Plasma Physics
October 29 to November 2, 1984

Category Number and Subject 4-9-1 Gyrotrons and Cyclotron Masers.

[X] Theory   [ ] Experiment

Theoretical Description of Orbitron Maser*
IGOR ALEXEFF, E.E. DEPT., UNIVERSITY OF TENNESSEE,
KNOXVILLE 37996-2100. --A theoretical description of
orbitron[1,2] operation has been made using a forward
travelling-wave line to simulate a cavity and a thin
electron ring to represent the confined electrons. We
find that unstable roots occur above the harmonics of
the electron electrostatic gyrofrequency, and that the
growth rate increase is linear with harmonic number.
The basic equation and dispersion graph are shown
below.

$$\frac{\ell^2}{L_o C_o \omega_2{}^2} + \frac{Z e a \ell^2 \omega_o{}^2 n_o}{C_o V_o / \ell n(r_2/r_1)(\omega_2 - \ell \omega_o)^2} = 1$$

If Z is -, V_o is + and conversely.

L_o, C_o, n_o in units per radian.

The equation has been extended to a Vlasov formalism,
$f(\omega_o)$, and will be discussed in detail.

1. Igor Alexeff and Fred Dyer, Phys. Rev. Letters 45,
351 (1980). 2. Y. Y. Lau and D. Chernin, Phys. Rev.
Letters 52, 1425 (1984).

[ ] Prefer Poster Session
[ ] Prefer Oral Session
[X] No Preference
[ ] Special Requests for placement of this abstract:
[ ] Special Facilities Requested (e.g., movie projector)

Submitted by:

Igor Alexeff
(signature of APS member)

Igor Alexeff
(same name typewritten)
EE Dept., Univ of TN
Knoxville, TN 37996-2100
(address)

This form, or a reasonable facsimile, plus *Two Xerox Copies* must be received
NO LATER THAN Noon, Friday, July 13, 1984, at the following address:

Division of Plasma Physics Annual Meeting
c/o Ms. Barbara Sarfaty
Princeton Plasma Physics Laboratory
P. O. Box 451
Princeton, New Jersey 08544

Category Number and Subject 4.9.1 Gyrotrons and Cyclotron masers

[x] Theory   ☐ Experiment

Cavity Modes-Electron Beam Interaction in the Orbitron Masesr*. WLODEK NAKONIECZNY AND IGOR ALEXEFF, E.E. DEPT., UNIVERSITY OF TENNESSEE, KNOXVILLE, 37996-2100. --The electron beam in the Orbitron's cavity[1] is approximated with electrons executing circular orbits. Integration of the Vlasov equation by the method of characteristics provides currents which are used as a source term in the equation describing time evolution of the cavity modes. The solution can be assumed in the exponential form, when modes interact little with each other. Further, conditions under which cavity modes are either supported (exponential growth) or damped (exponential decay) by the electron beam are studied.

1. Igor Alexeff and Fred Dyer, Phys. Rev. Letters, 45, 351 (1980).

☑ Prefer Poster Session
☐ Prefer Oral Session
☐ No Preference
☐ Special Requests for placement of this abstract:
☐ Special Facilities Requested (e.g., movie projector)

Submitted by:

(signature of APS member)

Igor Alexeff
   (same name typewritten)
E.E. Dept., Univ. of TN
Knoxville, TN 37996-2100
          (address)

Abstract Submitted
For the Twenty-Sixth Annual Meeting
Division of Plasma Physics
October 29 to November 2, 1984

Category Number and Subject 4-9-1 Gyrotrons and Cyclotron Masers

☐ Theory   ☒ Experiment

Submillimeter Operation and Efficiency of the
Orbitron Maser* FRED DYER, IGOR ALEXEFF, HAMID F.
KARIMY AND WLODEK NAKONIECZNY, E.E. DEPT., UNIVERSITY
OF TENNESSEE, KNOXVILLE, TN 37996-2100 --Since the
Orbitron[1] does not require a magnetic field, submil-
limeter operation is possible without large expensive
magnets. We are now operating at 0.7mm(430 GHz) with
a power of about 200 mW received at the detector.
At lower frequency(10 to 100GHz), output power is
about 50 watts. Power and efficiency are improved by
optimizing the cavity for higher Q and by correctly
locating the wire. Our optimized 30 GHz Orbitron has
an efficiency of about 5%. By reversing the tube's
polarity (making the wire negative), ions are trapped
in orbit around the wire. These ions also exhibit
negative mass instability and RF is emitted at a
frequency that is a factor of $\sqrt{1800}$ lower than the
frequency of orbiting electrons. A low frequency
tunable maser with an external tuned circuit has also
been used to study spectrum characteristics.

1. Igor Alexeff and Fred Dyer, Phys. Rev. Letters 45,
   351 (1980)

*Work supported by grant AF-AFOSR-82-0045-Alexeff.

☐ Prefer Poster Session

☐ Prefer Oral Session

☒ No Preference

☐ Special Requests for placement
  of this abstract:

☐ Special Facilities Requested
  (e.g., movie projector)

Submitted by:

(signature of APS member)

Igor Alexeff
(same name typewritten)
E.E.Dept., Univ. of Tenn.
Knoxville, TN 37996-2100
(address)

This form, or a reasonable facsimile, plus *Two Xerox Copies* must be received
NO LATER THAN Noon, Friday, July 13, 1984, at the following address:

Division of Plasma Physics Annual Meeting
c/o Ms. Barbara Sarfaty
Princeton Plasma Physics Laboratory
P. O. Box 451
Princeton, New Jersey   08544

Category Number and Subject <u>4.9 Coherent Radiation Generation</u>

☐ Theory   ☒ Experiment

<u>Probing the Pulsed Orbitron Glow Discharge</u>*, IGOR ALEXEFF, FRED DYER, and MARK RADER, <u>University of Tennessee 37996-2100</u> -- To study the suggestion that the pulsed Orbitron emission is due to plasma oscillations[2], we have probed the plasma with a microwave signal from an external oscillator. The result is that under the proper operating conditions, we can observe high frequency emission while a lower frequency probing beam shows no sign of cut-off. For example, we have observed orbitron emissions at a wavelength of 4 mm or shorter, with a penetrating beam at 9 mm. This suggests that under specific conditions, plasma oscillations are not the emission mechanism. Similar conclusions have been obtained by using both passive optical probing, and a Langmuir Probe.

1. I. Alexeff, Phys. Fluids, 28, 1990, June 1985.
2. R. W. Schumacher and R. J. Harvey, Bull. A.P.S., 29, 1179, October, 1984; R. W. Schumacher and R. J. Harvey, 1984 IEEE International Conference on Plasma Science, Conference Record, P. 109, IEEE Publication No. 84ch 1958-8.

☐ Prefer Poster Session

☐ Prefer Oral Session

☒ No Preference

Special Requests for Placement of
this Abstract:_____

Special Facilities Requested (e.g., movie
projector):_____

Submitted by:

(Signature of APS Member)

<u>Igor Alexeff</u>
(Same Name Typewritten)
<u>Department of Electrical Engineering</u>
<u>University of Tennessee,   37996-2100</u>
(Address)

This form, or a reasonable facsimile, plus TWO XEROX COPIES, must be received by NO LATER THAN NOON, Friday, July 18,1986, at the following address:

Ms. Dana Richards
L-630
Lawrence Livermore National Laboratory
P. O. Box 5511
  7000 East Avenue
  Livermore, CA 94550
(415) 422-9858

73

Abstract Submitted for the
1985 IEEE International Conference on Plasma Science

600 GHz Operation and Improved Construction of the Orbitron Maser[*] Fred Dyer and Igor Alexeff, Electrical Engineering Dept., University of Tennessee, Knoxville, TN 37996-2100 -- The Orbitron Maser[1,2,3] is a microwave source with negative mass unstable electrons electrostatically trapped around a small positive wire. A magnetic field is not required so high frequency operation is not limited as in conventional devices such as gyrotrons. A small magnetic field in fact kills maser action. We have recently achieved 600 GHz (0.5 mm) with an output power of at least 200 mW. This particular Orbitron has a wire diameter of 3 mils (.003 in.) and the threshold voltage for 600 GHz operation is about 21 KV. This corresponds to a second harmonic of the maximum electron orbiting frequency mode. Operation at 300 GHz (1 mm) is quite reliable with a power output of at least 2 watts. The next goal is to increase frequency to over 1000 GHz (.3 mm). This requires etching steps in wires that are 1 mil or smaller in diameter. The highest frequency generated increases linearly as wire diameter decreases. We have found that thoriated tungsten is much easier to handle and etch than the more expensive pure tungsten. A new design has been implemented that makes the structure more rugged with small wires and simplifies cavity design. Pre-ionization before the main current pulse reduces external arcing and improves repeatability.

----

1. Igor Alexeff and Fred Dyer, Phys. Rev. Letters. 45, 351 (1980).
2. Igor Alexeff and Fred Dyer, 1983 International Conference on Infrared and Millimeter Waves. F2.4, CH 1917-4/83/0000-0F24.
3. Igor Alexeff, IEEE Trans. on Plasma Science, PS-12 No. 4, 280 (1984).

Subject category and number:

18. High-Power Microwave and

Submillimeter Wave Generatic

☐ Prefer oral session

☐ Prefer poster session

☒ No preference

Submitted by:

Francis F Dyer
signature

Francis F Dyer
same name typewritten

University of Tennessee
company

Electrical Engineering Dept.
address

Knoxville, TN 37996-2100
city, state, zip

(615) 974-6223
telephone

Important:

Category Number and Subject ____4.9.1____   Coherent radiation
generation - Gyrotrons
☐ Theory   ☒ Experiment   and cyclotron masers.

Recent Results for Oribitron Electrostatic Maser.*
Igor Alexeff, Fred Dyer, Hamid F. Karimy and Wlodek
Nakonieczny, E.E. Dept., University of Tennessee, ---
Our maser[1] now generates steady-state, narrow - band
microwaves in the 30 to 1 centimeter range, as measured
by an Integra YIG - tuned panoramic receiver. The out-
put consists of lines that generally correspond to the
predicted resonances of the microwave cavity. The
exception is the lowest - frequency line, which corre-
sponds closely to the plasma frequency, and is density
-tuneable. In pulsed operation, we have increased
power output and reliability of operation up to our
diagnostic limit of 2 millimeters. Also, we are now
successfully extracting almost all the radiation
through a waveguide attached to the cavity.

[1]Igor Alexeff and Fred Dyer, Phys. Rev. Letters 43,
351 (1980).

☐ Prefer Poster Session   Submitted by:

☒ Prefer Oral Session

☐ No Preference   (signature of APS member)

☐ Special Requests for placement
of this abstract: Igor Alexeff
(same name typewritten)

☐ Special Facilities Requested
(e.g., movie projector)   University of Tennessee
(address)

This form, or a reasonable facsimile, plus *Two Xerox Copies* must be received
NO LATER THAN Noon, Friday, July 15, 1983, at the following address:

Division of Plasma Physics Annual Meeting
c/o Ms. Barbara Sarfaty
Princeton Plasma Physics Laboratory
P. O. Box 451
Princeton, New Jersey   08544

Steady-State Orbitron Emissions

MARK RADER, STUDENT MEMBER, IEEE, FRED DYER, MEMBER, IEEE, AND IGOR ALEXEFF, FELLOW, IEEE

Abstract—The Orbitron maser has been operated at a pressure of 2 × 10⁻⁶ in the steady state. Electrons are supplied to the device by an oxide-coated tungsten cathode placed inside the cylindrical cavity. The plasma-free emission corresponded to harmonically related steady-state narrow lines. The fundamental (lowest frequency) line corresponds to a resonance in the cavity system, which could be observed with a grid-dip meter.

(a)

I. INTRODUCTION

ON September 3, 1985, the first steady-state high-vacuum Orbitron maser [1] emissions were observed. These emissions were from a device in a high vacuum of 5×10^{-6} torr produced by an oil diffusion pump trapped by a liquid-nitrogen-cooled baffle. The electron feed for this device was provided by an axial hot cathode in a cylindrical cavity. To demonstrate that no plasma was present to produce plasma oscillations, as claimed by others [2], [3], we monitored the presence of plasma in the cavity of this tube and many of the subsequent devices with a Langmuir probe. This device has since undergone many design revisions as the design theory has been better understood. These changes include multiple anode wires, changing the electron feed system, and the suppression of low-frequency resonances by excluding large orbit electrons from the device. This paper will describe these experiments and others using a gas-filled pulsed Orbitron.

II. THEORY

The Orbitron operates by means of a very simple physical mechanism. Electrons are injected into a coaxial system in which there is a potential well present. These electrons, because of their angular momentum, orbit the central wire, and generate radiation as they lose energy and fall closer to the wire. The physical mechanism by which the Orbitron generates radiation is known as a negative mass instability. This is the same mechanism by which gyrotrons [4] operate, but important differences lie in the types of electron confinement used in this device and in the electron kinetic energies involved. In order to explain these differences and how this device works, one must look at the basic Orbitron configuration as illustrated in Fig. 1(a). The internal structure of the Orbitron is characterized by a wire radius r_0, a wall radius r_1, and a dif-
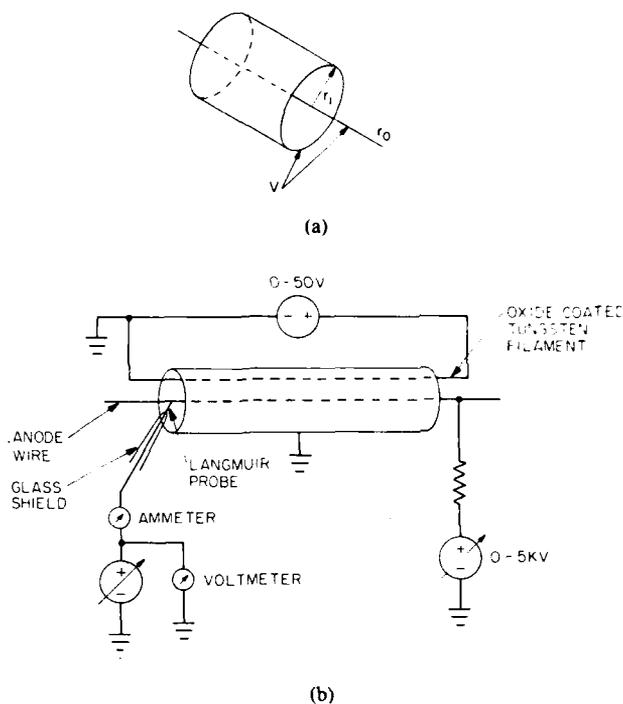
(b)

Fig. 1. (a) Basic Orbitron diagram. (b) Orbitron schematic.

ference in potential V between the inner conductor (V_{wire}) and the outer cavity (V_{wall}). The difference in potentials is such that $V_{\text{wire}} > V_{\text{wall}}$. Electrons injected into this system are electrostatically confined in a potential well and orbit the central wire in a natural population inversion. This population inversion is caused by the loss of electrons from the system through impact on the wire. This system is also naturally negative mass unstable and so can use electrons with a low kinetic energy [1]. This is in contrast to the relativistic energies required by gyrotrons to achieve a negative mass instability. The gyrotron also requires an electron dumping mechanism needed to achieve a population inversion while the Orbitron has this as a natural result of its confinement system. The term negative mass comes from the fact that, in this system, as the electrons lose energy they fall in orbital radius and gain orbital angular velocity [4].

The Orbitron also has an advantage in frequency range over the gyrotron. For circular electron orbits, the highest angular frequency $(w)^1$ an Orbitron will produce is given by

$$w = 1/r_0 \times \left(eV \left(m \times \ln \left(r_1/r_0 \right) \right)^{-1} \right)^{1/2}.$$

This only differs from highly elliptical orbits by a factor
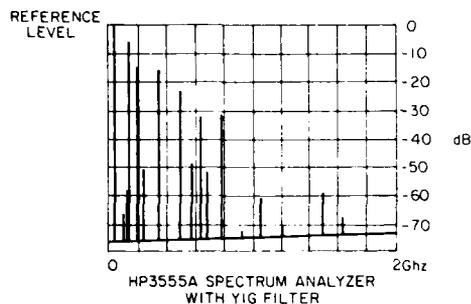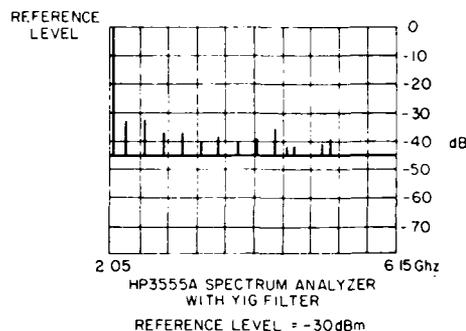
Fig. 2. First Orbitron spectra.

(a)

(b)
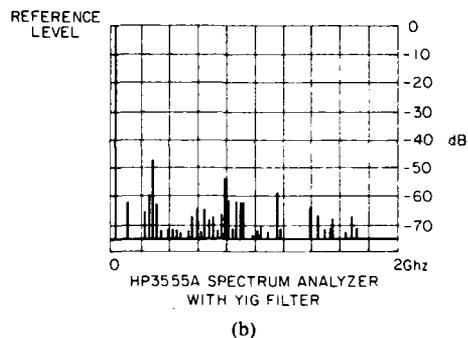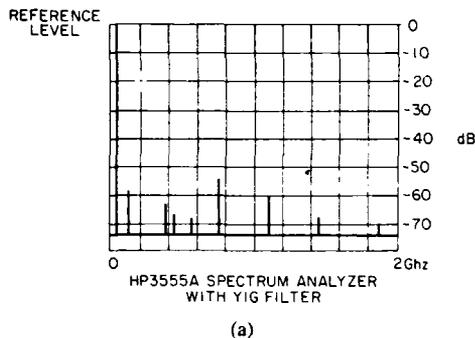
Fig. 3. (a) One-wire comparison. (b) Two-wire comparison.
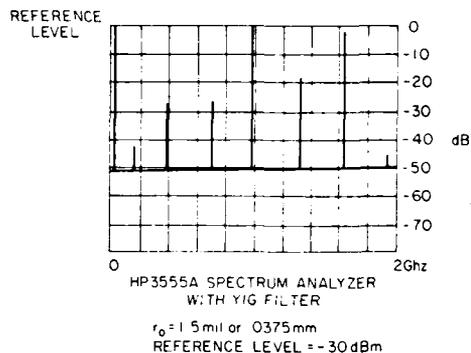
of $(\pi/2)^{1/2}$. So the frequency is only limited by the highest voltage available and the size of the center wire [5]. In a gyrotron the frequency is limited by the magnitude of the magnetic field that can be produced. The highest possible angular frequency of a gyrotron is eB/m_e. A pulsed magnetic field of approximately 24 T is the strongest magnetic field that has been obtained in this type of device. This corresponds to a wavelength of about $\frac{1}{3}$ mm[6].

III. STEADY-STATE EMISSIONS

On September 3, 1985, the first high-vacuum orbitron emissions were observed. These emissions have led to a series of proof of principle experiments. There have been three distinct groups of these experiments, and these are what will be explored.

In the first group of experiments, open cavities between 5 and 10 cm in length were used with a diameter of between 1 and 2 cm. These cavities generated a series of

Fig. 4. Four-wire spectra.

Fig. 5. Seven-wire spectra.

harmonics for which the fundamental was determined by an external cavity cable resonance. Fig. 2 shows the first of these experiments. It was operated at a pressure of 5 $\times$ 10^{-6} torr at a wire potential of 500 V and a current in the center wire of 40 mA. The radius of the center wire was 3 mils or 0.075 mm.

This cavity and subsequent cavities of this group of experiments were monitored for the presence of plasma with a Langmuir probe. There were no indications of a plasma except for a few microamperes of electron current, which originated from the hot filament. The next step was to increase the number of anode wires from one to two. This was done in the belief that this would increase the power output and the frequency range.

Fig. 3 is a comparison between one and two center wires. The pressure was at 5 $\times$ 10^{-6} torr and the voltage in the top spectral picture was 1.2 kV, while at the bottom it was 800 V. Both had a current of about 34 mA on the center wire. Some nonharmonic frequencies can be seen in the two-wire spectral picture. These go away as the current or the voltage is increased and what appears to be phase locking occurs between the wires.

The number of center wires was increased to four and the power and the apparent phase locking increased significantly, but more importantly, the frequency of emission went up sharply. Fig. 4 is an example of this. The input operating voltage to this device was 500 V, and the current through the center wire radius was 3 mils or 0.075 mm. Under these operating conditions the highest circular
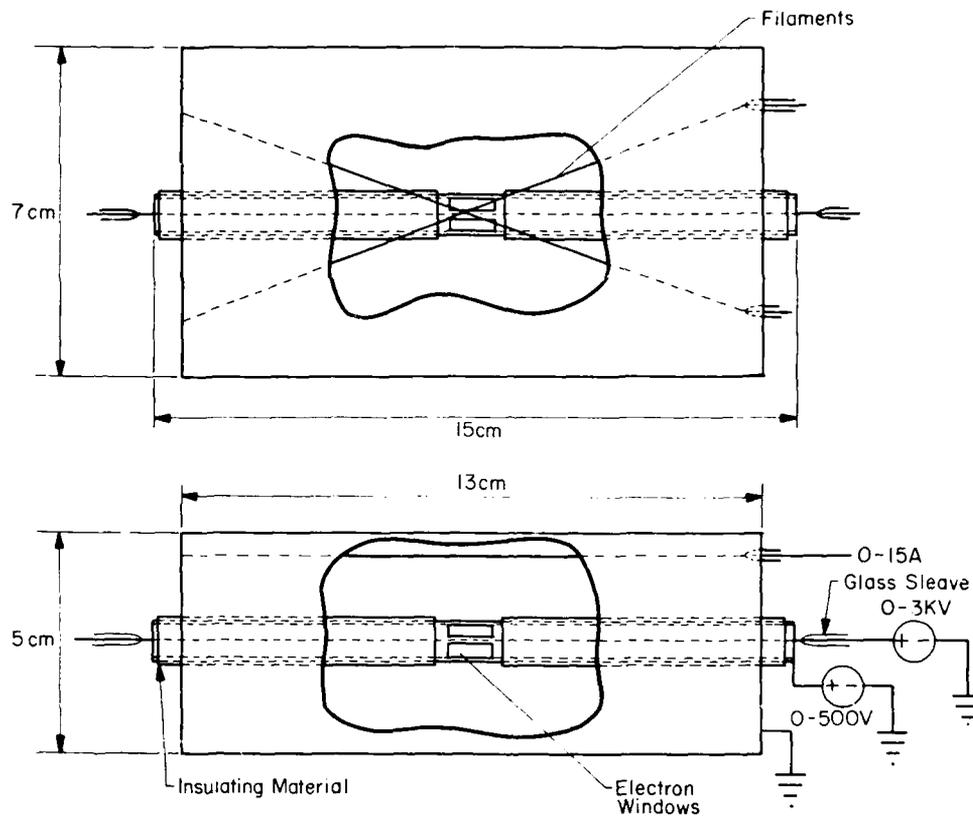
Fig. 6. Double cavity schematic.

frequency is 8.3 GHz, and so this is within a factor of 1.5 of what is shown below.

In the next experiments, the number of center wires was increased to seven. It significantly increased the output amplitude, as seen in Fig. 5, with less current required for what appears to be phase locking. In Fig. 5 the center wire voltage was 500 V at 20 mA. The pressure was 2 × 10^{-6} torr.

In the second group of experiments an attempt was made to control the fundamental frequency by changing the cavity structure. In order to do this, it was necessary to reduce the cavity radius so that large low-frequency orbits would not fit inside the cavity at low to moderate voltages. This was accomplished by constructing the double cavity system shown in Fig. 6.

This device met with limited success. While it was possible to control the fundamental frequency with a cavity mode, as demonstrated in Fig. 7, it required an accelerating voltage on the secondary cavity and had very small wire currents.

In the third group of experiments, the configuration was changed back to the original design with a cavity length of 15 cm, but the reduced cavity radius was kept. This worked extremely well. The frequencies observed corresponded to the fundamental TEM modes of the cavity. This was observed on two receivers, as demonstrated in Figs. 8 and 9. The power output from this device was greater than previously observed and in some cases was
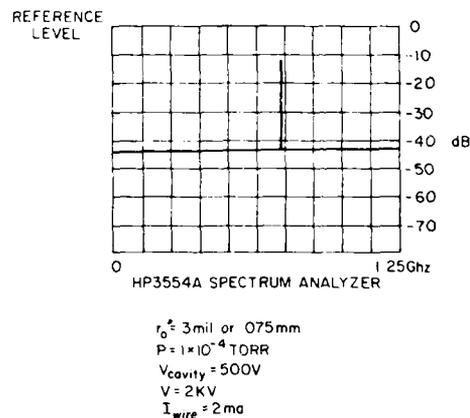

Fig. 7. Double cavity spectra.

seen to be −10 dBm at one frequency, as seen in Fig. 9, with a correction for horn and cable losses included. This is the power observed impinging on the receiving horn, and not that radiated over all space. Assuming that the power is radiated uniformly over free space and knowing the horn area (0.391 m²), the radius from which the data were taken (0.15 m), and the power used by the device (4.2 W), it is possible to estimate the efficiency of the device which is about 0.01 percent, but this is only the efficiency at one frequency. To get the overall efficiency one must take into account the power radiated at other frequencies.
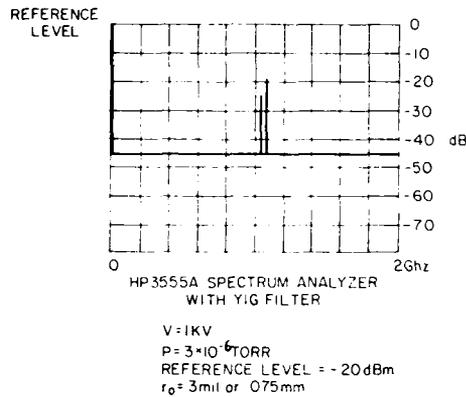
HP 3555A SPECTRUM ANALYZER
WITH YIG FILTER

V = 1 KV
P = 3×10⁻⁶ TORR
REFERENCE LEVEL = -20 dBm
r_0 = 3 mil or 075 mm

Fig. 8. Hewlett-Packard spectra.

INTEGRA SPECTRUM ANALYZER

V = 1.3 KV
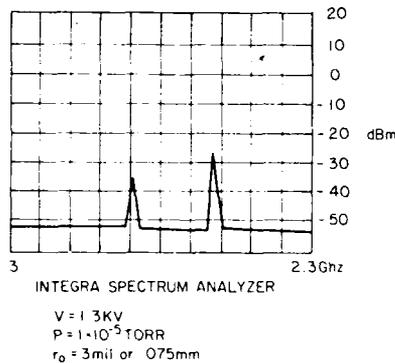P = 1×10⁻⁵ TORR
r_0 = 3 mil or 075 mm

Fig. 9. Integra spectra.

In these devices, it has been found that a difference in potential of only 40 V is required for noticeable emission to occur with a starting current of about 8 mA, but this starting current was reduced to the order of 0.5 mA or less as the voltage was raised to 300 V or higher. This start current appears to be highly dependent upon the Q of the resonant system [5]. To eliminate the possibility of signal imaging and spurious responses in our spectral analysis, a YIG-tuned filter or other filter designed to eliminate aliasing was attached to the spectrum analyzers when necessary.

IV. PULSED EMISSIONS

The pulsed Orbitron appears to work by the same mechanism as the steady-state Orbitron except that electrons are supplied by a cold cathode discharge which ionizes any gas in the tube. Ions are collected by the cathode wall and electrons from the gas are trapped in orbit around the positive central wire and cause the Orbitron effect. The gas pressure in these tubes ranges from 50 to 0.1 mtorr, depending on the tube.

While the operating mechanism of the steady-state version of this tube appears to be well understood, there are still some questions about the operating mechanism of the pulsed device [2], [3]. To dispel these doubts, there has been a series of experimental attempts to ensure that the operating mechanism is properly understood.

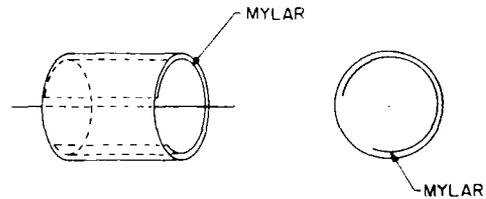The experimental work included probing the working

Fig. 10. Insulated cavity.

tube with a microwave signal to determine the plasma cutoff frequency. This was found to be as low as one quarter of the emitted frequency. This suggests that plasma oscillations are not the fundamental emission process. Also tried was lining $\frac{9}{10}$ of the cathode tube with a high-voltage insulating material, as shown schematically in Fig. 10, to eliminate two-beam plasma interactions which were suggested as the fundamental emission mechanism [2], [3]. In this experiment, it was found that with all other conditions the same, there is little to no change in the emission characteristics.

In this pulsed gas-filled tube, a much higher voltage can be used, as well as a thinner wire. In this mode of operation, detection of submillimeter wavelengths is routine, and we have obtained radiation at 1 THz (0.3 mm). The peak microwave power output is about 1.5 W at 1 THz and about 50 W at frequencies around 100 GHz. Efficiencies range from 1 percent at 3.5 GHz to 0.001 percent at 1 THz [7]. While the power may seem low, it must be remembered that many of these frequencies are emitted simultaneously from one tube with the same power levels.

V. CONCLUSION

It has been demonstrated that the steady-state Orbitron is an operational device, and that it appears to operate in the way our assumptions predict. There is evidence that the pulsed Orbitron also works according to the same theory. Both the pulsed and steady-state Orbitrons offer an alternative to the main-line concepts now in use for high-frequency microwave production. In these experiments, many of the concepts of the steady-state Orbitron have been introduced and shown to hold true. While the steady-state frequency limit demonstrated is not yet that of the pulsed Orbitron, it is believed that this can be improved to higher frequency ranges.

REFERENCES

[1] I. Alexeff and F. Dyer, Phys. Rev. Lett., vol. 45, p. 351, 1980.
    I. Alexeff, IEEE Trans. Plasma Sci., vol. PS-12, p. 2880, 1984.
    I. Alexeff, Phys. Fluids, vol 28, p. 1990, June 1985.
[2] R. W. Schumacher and R. J. Harvey, in Proc. 1984 IEEE Int. Conf. Plasma Sci. (IEEE Pub. 84ch 1958-81, p. 109.
[3] R. W. Schumacher and R. J. Harvey, Bull. Amer. Phys. Soc., vol. 29, p. 1179, Oct. 1984.
[4] D. Chernin and Y. Y. Lau. "Stability of laminar electron layers," Phys. Fluids, vol. 28, Sept. 1984.
[5] J. M. Burke, W. M. Manheimer, and E. Ott, Phys. Rev. Lett., vol. 56, p. 2625, June 16, 1986.
[6] G. Nusinovich (Inst. Appl. Phys., Gorky, USSR), private correspondence, Dec. 1985.
[7] I. Alexeff, F. Dyer, and W. Nakomeczny, Int. J. Infrared Millimeter Waves, vol. 6, no. 7, p. 481, 1985.

TIME DEPENDENT FREQUENCY SHIFT IN THE ORBITRON MASER*

Igor Alexeff, Fred Dyer, Mark Rader, University of Tennessee 37996-2100:

It has been observed by both ourselves and others[1], that the frequency output in our pulsed Orbitron maser chirps upward in time as the discharge voltage declines. This is explained by the way the Orbitron operates. The Orbitron maser[2] is a device in which electrons orbit a positively charged central wire placed on axis in a cavity resonator. The rotating electrons couple to microwave cavity modes and generate RF radiation. These electrons are born on the outer edge of the cavity-wire system and drift inward. Since the frequency output of the electron is inversely proportional to the electron radius in the system, and the electron cloud must move inward into the potential well to obtain the work required for microwave emission, one would expect to see a shift upward in frequency as the pulse progresses even though the potential well is collapsing.

We have predicted this upward frequency chirp from the basic theory of this device and have found it to be in good agreement with what we experimentally observe. Using standard charcteristics of these devices, the chirp rate has been found to be 3.55×10^{17} Hertz per second, and in a characteristic experiment, using a device of the same dimensions as was used in our calculations, we get a chirp rate of 5.5×10^{17} Hertz per second.

1. R.W. Schumacher and R. J. Harvey, Bull. A.P.S., 29, 1179, October, 1984: R. W. Schumacher and R. J. Harvey, 1984 IEEE Internatoinal Conference on Plasma Science, Conference Record, P 109, IEEE Publication No 84ch 1958-8: Private conversation with R. W. Schumacher.
2. I. Alexeff, Phys. Fluids, 28, 1990, June 1985.

CROSS SECTIONAL NUMBER DENSITY IN THE PULSED ORBITRON MASER* Mark Rader, Igor Alexeff and Fred Dyer, University of Tennessee 37996-2100

To study the suggestion that the pulsed Orbitron emission[1] is due to plasma oscillations[2], we have probed the plasma with a microwave signal from an external oscillator. The result is that under the proper operating conditions, we can observe high frequency emission while a lower frequency probing beam shows no sign of cut-off. For example, we have observed orbitron emissions at a frequency of 133 GHz or higher, with a penetrating beam at 36 GHz. This gives a emission to bulk plasma frequency ratio of 3.7 to 1. We have also used a radially adjustable Langmuir Probe to study the electron number density at points across the discharge radius. The peak electron plasma frequency in this device at a radius of 40 mils (1 mm) was found to be about 10.6 GHz. The peak frequency emitted by this device was found to be 38 GHz. This gives a peak emission to peak plasma frequency ratio of 3.6 to 1. The peak number density occurs between .5 to 1 microseconds after the peak emission occures.

The electron temperature at this point was about 25 eV with a plasma potential (V_p) of 150 V. Since the Orbitron maser is a coaxial system with a positively charged wire at the center, 10 kV in this case, this plasma potential indicates a potential well for electron trapping.

1. 1. Alexeff, Phys. Fluids, 28, 1990, June 1985.
2. R. W. Schumacher and R. J. Harvey, Bull. A.P."S., 29, 1179, October, 1984: R. W. Schumacher and R. J. Harvey, 1984 IEEE International Conference on Plasma Science, Conference Record, P 109, IEEE Publication No 84ch 1958-8.

Category Number and Subject   4.19 High Power Microwaves

☐ Theory   ☒ Experiment

Average and Cross Sectional Number Densities in the Orbitron Maser*, Mark Rader, Fred Dyer, and Igor Alexeff, University of Tennessee, 37996-2100: In order to better understand the pulsed glow Orbitron MASER, we have been using a penetrating microwave beam to make bulk measurement of the number density in the plasma. The result is that under the proper operating conditions, we can observe high frequency emission while a lower frequency probing beam shows no sign of cut-off. For example, we have observed orbitron emissions at a frequeny of 250 GHz or higher, while a microwave beam at 37.5 GHz was penetrating the glow discharge. This gives a emission to bulk plasma frequency ratio of 6.7 to 1. We have also used a radially inserted Langmuir probe to measure both the electron number density across the plasma chord and the electron temperature. From this probe we found the peak electron plasma frequency in this device at a distance of 40 mils (1 mm) from the central wire was about 10.6 GHz. The peak frequency emitted by this device was found to be 38 GHz. This gives a peak emission to peak plasma frequency ratio of 3.6 to 1. These and other experimental results lead us to conclude that the emitted frequency is apparently not related to the electron plasma frequency.
*Work supported by the Air Force Office of Scientific Research under grant AF-AFOSR-86-0100.

☐ Prefer Poster Session
☒ Prefer Oral Session
☐ No Preference
☐ This poster/oral should be placed in the following grouping: (specify order)

_____

☒ Special Facilities Requested (*e.g.*, movie projector)
   slide projector

☐ Other Special Requests

_____

Submitted by:

_____
(Signature of APS Member)

Igor Alexeff
(Same Name Typewritten)

409 Ferris Hall
(Address)
Univ. of Tenn.   37996-2100

This form, or a reasonable facsimile, plus **TWO XEROX COPIES**, must be received by **NO LATER THAN NOON**, Friday, July 17, 1987 at the following address:

Ms. Barbara Sarfaty
Princeton Plasma Physics Laboratory
P.O. Box 451
Princeton, NJ 08544
(600) 683-2440

82