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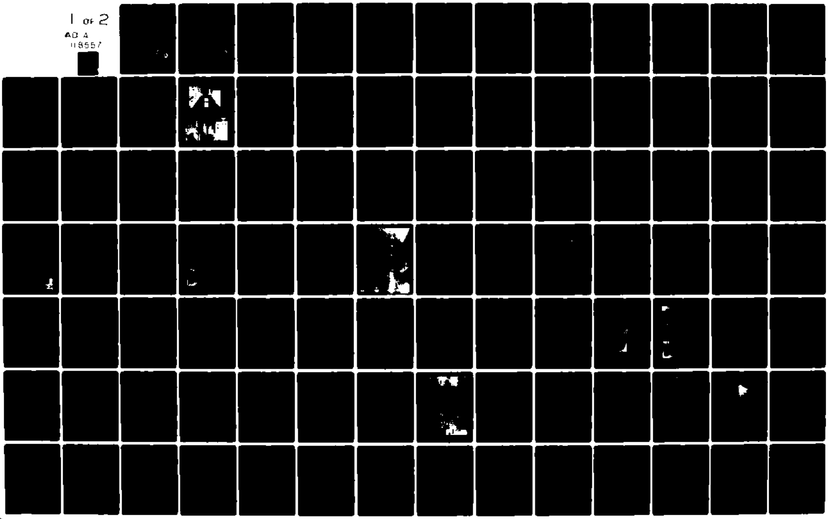

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INTERIM SCIENTIFIC REPORT

ON

Contract AFOSR 81-0093

March 15, 1981 to June 30, 1982

J. Reece Roth

Principal Investigator

UNCLASSIFIED

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This interim report summarizes accomplishments supported by AFOSR Contract No. 81-0093 during the period March 15, 1981 to June 30, 1982. During this initial phase of the contract, an electric field dominated plasma facility was designed, assembled, and put into operation. It consists of a steady state Penning discharge operating in a water-cooled magnet system which is capable of up to 0.4 Tesla. The high voltage power supply, magnet system, cooling water, and vacuum system have been assembled, and the first plasma was achieved.

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Diagnostic systems which have been put into operation thus far include spectrum analyzers to examine RF emissions to 28 GHz and a retarding potential energy analyzer. The plasma has operated for hours at a time, has exhibited a broad-band RF white-noise spectrum over frequencies from 0.5 MHz to 1.0 GHz; has produced ions with characteristic energies along the field lines of several hundred electron volts; and has exhibited evidence of strong parallel electric fields in the plasma. This plasma promises to be a rich source of information and data on physical processes in electric field dominated plasmas.

Interim Scientific Report

Interim Report on Contract AFOSR 81-0093 for the Period

March 15, 1981 to June 30, 1982

Submitted to

THE AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

by

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UTK Plasma Science Laboratory
Report No. 82-2

July 20, 1982

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Principal Investigator

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ABSTRACT

This interim report summarizes accomplishments supported by AFOSR Contract No. 81-0093 during the period March 15, 1981 to June 30, 1982. During this initial phase of the contract, an electric field dominated plasma facility was put into operation. It consists of a steady-state Penning discharge operating in a water-cooled magnet system which is capable of 0.4 Tesla. The high voltage power supply, magnet system, cooling water, and vacuum system have been assembled, and the first plasma was achieved. Diagnostic systems which have been put into operation thus far included spectrum analyzers to examine RF emissions from 0.5 MHz to 28 GHz, and a retarding potential energy analyzer. The plasma is capable of operating for hours at a time; has exhibited a broad-band RF white-noise spectrum over frequencies from 0.5 MHz to 1.0 GHz; has produced ions with characteristic energies along the field lines of several hundred electron volts; and has exhibited evidence of strong parallel electric fields in the plasma. This plasma promises to be a rich source of information on physical processes in electric field dominated plasmas.

RESEARCH PROGRAM

Objectives

This research program was initiated on March 15, 1981, and at the present writing has been under way for 16 months. It is supported by AFOSR contract 81-0093 under NP program manager Dr. Michael A. Stroscio of the Bolling Air Force Base. This contract was a new start at the University of Tennessee, Knoxville, and is an important part of an effort at our institution to set up, in the UTK Plasma Science Laboratory, a research effort specializing in electric field dominated plasmas, and to investigate the physical processes associated with RF emissions and plasma heating and turbulence.

The objectives of this contract have been as follows:

1. To assemble and put in operation a steady-state Penning discharge which creates an electric field dominated plasma penetrated by strong radial and axial electric fields.
2. The operation of this Penning discharge under conditions that exhibit phenomena of interest, including radio frequency emissions at the geometric mean emission frequency and other frequencies; anomalous plasma resitivity; and plasma, particularly ion, heating by the application of raw DC electrical power.
3. Investigation of the most effective electrode geometry, magnetic mirror ratio, and plasma operating conditions to produce the phenomena of interest.
4. Development of dedicated plasma diagnostic instruments for measurement of the phenomena of interest, where such instruments are not already in the inventory of the UTK Plasma Science Laboratory. Such instruments

which are already in place or under development include a retarding potential energy analyzer, a computer program to reduce and analyze the analog data from this instrument; a Langmuir probe for the measurement of the longitudinal (along the magnetic field) potential distribution and electric field strength; and a microwave interferometer.

5. Measurement of the parallel and perpendicular plasma resistivity, and a comparison of these values with theoretical predictions.

6. Exploratory studies of RF emission, to determine whether any unanticipated phenomena are present.

Possible Utility of Research to the Air Force

The initial focus of our research efforts will be phenomena related to the geometric mean emission frequency, a recent discovery of Roth and Alexeff (ref. 2). The frequency of the geometric mean plasma emission can be written in terms of the plasma electron number density and the atomic mass number A of the ion species as follows, where ν_{GM} is

$$\nu_{GM} = .537\sqrt{\nu_{pe}\nu_{pi}} = \frac{737\sqrt{n_e\ (cm^{-3})}}{A^{1/4}}\ \text{Hz} \tag{1}$$

RF emission at this frequency has been observed in the modified Penning discharge operated in conjunction with the ONR contract at the UTK Plasma Science Laboratory, and has also been apparent in the initial observations of the RF emissions from the classical Penning discharge configuration in the AFOSR experiment, as will be seen later.

It is possible that the geometric mean emission can be excited in the magnetosphere or in the ionsphere, due to an influx of mirroring or counterstreaming electrons. The emission frequency associated with maximum ionospheric densities and atomic oxygen ions falls within a range of 230 KHz to 1.6 MHz. The lower frequency limit could be much less than 230 kHz if the emission were excited at a plasma density less than the ionospheric maximum.

The experimental observations made thus far suggest several reasons why the geometric mean plasma emission might be of practical interest for communications or other purposes.

1. The geometric mean emission spans a region of interest for ground-based communications. It has been observed over the range from 12 to 350 megahertz. By variation of the ionic species of the emitting plasma, by operating a modified Penning discharge at higher density, and by generating very high mode numbers, it should be possible to cover a range from at least 10 megahertz to 20 gigahertz.
2. The geometric mean plasma emission may be excited by mirroring or counterstreaming electrons in the ionosphere or magnetosphere by natural processes associated with, for example, solar flares. If this occurs, frequencies from approximately 1.6 MHz down to very low frequencies could be excited, and these could interfere with military communications and/or low frequency navigation beacons.
3. The geometric mean plasma emission can be created in the atomospheric RF windows. As a transmitter, it therefore may be useful for such purposes as beacons, radar, ground-to-ground and space-to-ground communications, jamming, etc.
4. The emitting electrons and ions are trapped in the modified Penning discharge by a combination of electrostatic and magnetic trapping. The average particle lifetime is much longer than a single transit time, in constrast to traveling wave tubes where the emitting electrons are not trapped, and pass once through the traveling wave tube

in a single transit time. The trapping of electrons and ions in the emitting volume may lead to much higher efficiencies than are possible in once-through devices like traveling wave tubes.

5. The penetration of plasmas confined in modified Penning discharges by strong radial and axial electric fields is well known. These electric fields allow the radiating ion and electron populations to be coupled directly to an external dc power supply, thus imparting energy to the radiating species in the same volume in which the RF emission originates. This contrasts with traveling wave tubes, where the electrons are accelerated to higher velocity in an electron gun that is remote from the region in which the radiation originates. The factor may also lead to higher efficiencies than are possible with traveling wave tubes.

6. The electric field dominated plasmas which produce the geometric mean plasma emission have two interpenetrating beams of electrons interacting with the background plasma, and the resulting higher level of plasma turbulence gives rise to much lower conductivities than are associated with the Buneman single-beam-in-plasma mechanism. For deuterium, the two-beam instability gives rise to conductivities 176 times lower than the Buneman value. Such low conductivities may be useful in applications in which intense pulsed RF power is required (from the geometric mean mechanism); in which plasma power densities are required; or in which rapid ion heating is desired.

7. Exploratory investigations under this contract have shown that a classical Penning discharge (ref. 3), when operated with a plasma of argon gas, is capable of emitting broadband, white noise over

frequencies ranging from 0.5 megahertz to at least 1.0 gigahertz. This very broad-band emission may have applications to military jamming, or in understanding broad-band emission from magnetospheric or other sources.

8. The very strong axial electric fields in these Penning discharge plasmas, ranging up to 150 volts per centimeter, are capable of directly coupling the dc power supply to the plasma electron and ion populations. Thermalized ions with energies up to several kilovolts have been observed, and in related work on the ONR contract at the UTK Plasma Science Laboratory, a wide range of energy distribution functions have been observed, the detailed nature of which depends upon the operating conditions (ref. 4).

9. The Penning discharge is capable of producing energetic ions, with characteristic energies ranging up to several kilovolts, and distribution functions which can be varied at will from nearly monoenergetic, to maxwellian, to a flat distribution function with an even distribution of energies between 0 and some maximum energy (ref. 4). The availability of such an ion source may have applications to nuclear weapons simulation, the simulation of particle radiation fluxes in the magnetosphere, or materials testing.

PROGRESS REPORT

Assembly and Operation of Experimental Apparatus

All of the necessary formalities were complete in time for contract AFOSR-81-0093 to start on March 15, 1981. During the first year of this contract, only one half-time research assistant was budgeted. This assistant, Mr. Robert L. Pastel, joined us on April 28, 1981. Upon signing the contract, we were able to place orders for certain equipment, and arrange for the University to begin the plumbing and electrical work necessary to install the magnetic field coils for the AFOSR contract, at no expense to the Air Force. Mr. Pastel joined us about a month and a half after the contract started. This delay made available sufficenty money to hire a temporary research assistant half-time from mid-June to mid-August.

The magnets were manufactured by the Magnion corporation 20 years ago, and required extensive restoration and reconditioning. The coils are, at present, connected to produce a uniform magnetic field. This will be used in initial experiments and will later be modified to a mirror configuration in order to operate the plasma as a modified Penning discharge. The rectifier power supply for the coils was made by the Sel-Rex Corporation 20 years ago, and no documentation was available when this coil system was obtained as a donation from the Oak Ridge National Laboratory about 2 years ago. A complete wiring diagram was drawn up by Mr. Roger Richardson, our summer research assistant, who also repaired the control system. The power supply also has been hooked up to water and electrical power. The power supply was tested and produces 900 amps of direct current when connected to the coils.

The progress as of mid-October, 1981, can be seen in the before and after photographs on the next page. Figure 1 shows a photograph of the Air Force apparatus before the initiation of the contract. The Magnion coil system is in the middle of the room, with the water and electrical power unconnected. On Figure 2 is a photograph of the Air Force coil system and some peripheral equipment, after the electrical power and cooling water were connected, but before the vacuum system was installed. The vertical pipes in front of the coil system are a two-inch water main which provides cooling. The electrical cables which connect the coils to the power supply are under the wooden protective cover shown in the lower right foreground. On the right hand side of the photograph is the reconditioned coil power supply. On the floor to the left of the power supply, and in the background beside one of our senior lab students, is some equipment that had been assembled by mid-October for the vacuum system.

Final assembly and operation of the vacuum system was delayed until mid-February by the procurement of a special piece of 5 inch diameter glass pipe which threads the inner bores of the magnetic field coils. The vacuum system was fitted with a turbomolecular pump which was purchased with equipment money designated in the first year of the AFOSR contract. This pump operated satisfactorily for approximately 900 hours, and then suffered a bearing failure. This apparently was a design defect of the particular model, and the entire pump was replaced under warranty in late Spring, 1982, after approximately a 4 week delay. The first plasma was achieved in February, 1982, and this was followed by several weeks of exploratory investigations.

FIGURE 1

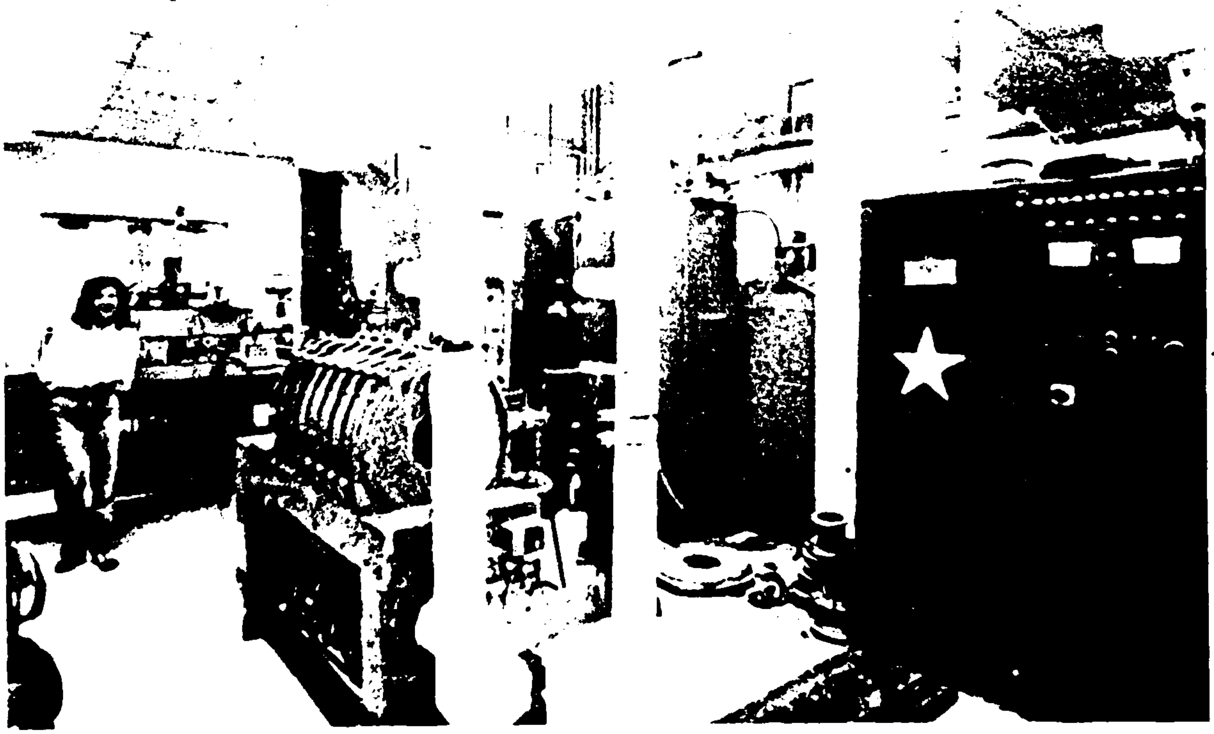


FIGURE 2

At this writing, the major sub-systems of the facility have been operated for relatively long periods of time, and have undergone an extensive period of shake-down and debugging. The 40 kV, 1 amp dc power supply used for the Penning anode ring, the water cooled magnetic field coil system and its power supply, the vacuum system, and the facility control and monitoring system are now operating in a trouble free manner.

Since achieving the first plasma, our first priority has been to bring on line the diagnostic instruments necessary for our research program. This proceeded rapidly, thanks to the facilities and equipment already available at the UTK Plasma Science Laboratory. On the same day we achieved the first plasma, it was possible to make measurements of the RF emission spectrum, since the spectrum analyzers required were mounted in a mobile equipment rack and were easily borrowed from the ongoing investigations for the ONR contract. A retarding potential energy analyzer, identical to that used in the ONR contract, was installed in the vacuum system, and, when required, connected to the same power supplies, ramping circuits, and xy recorder used for the ONR experiment. Available equipment was used to fabricate a high voltage Langmuir probe (needed because floating potentials up to 10 kV must be measured) for potential profile measurements. A microwave interferometer is being fabricated with equipment already available in the UTK Plasma Science Laboratory, and a data reduction program is being debugged which will be used in conjunction with our retarding potential energy analyzer data.

The renewal of this contract, which began March 15, 1982 provided for two half-time research assistants. Mr. Pastel was retained into the second year of the contract, and on April 1, 1982, a half-time research assistant, Mr. Gregory Hutchens, was hired, and given the primary responsibility for developing a computer software program to analyze the integrated ion energy distribution functions produced by the retarding potential energy analyzer.

Initial Experimental Results

During the period covered by this report, the AFOSR magnet facility was set up to produce a classical Penning discharge configuration, in which the magnetic field is approximately uniform along the axis of the discharge. This configuration lacks the magnetic field minimum in the vicinity of the anode of the discharge which is characteristic of the modified Penning discharge. The characteristics of the facility, a scaled drawing of the apparatus, and a longitudinal magnetic field profile are shown in Appendix B, pages B-39 to B-42. The classical Penning discharge illustrated on page B-41 was operated with a uniform magnetic field up to 0.3 tesla at the Penning anode, and produced a plasma about 10 centimeters in diameter and 70 centimeters long. The plasma was operated in the steady-state with helium and argon gas, and the glass vacuum system allowed RF radiation to escape.

Some of the initial experimental results are illustrated in the reports in Appendix B on page B-18 and B-19 and on pages B-43 to B-45. A spectrum of RF emission from 0 to 500 megahertz is shown on page B-43. This plasma appears to operate in only a single mode, and to produce spectra of which this figure is characteristic for both helium and argon gas. This example has 27 harmonics extending out to 500 megahertz, and harmonics have been observed under other conditions to 1 gigahertz. Many nonlinear mode coupling phenomena are apparent, including an example of plasma "lability" in which the spectral amplitude is greatest around the 8th harmonic at 200 megahertz. It may be that this maximum in the envelope of harmonics of the geometric mean emission frequency occurs at the electron plasma frequency for the discharge.

Additional results with the classical Penning discharge are illustrated on pages B-44 and B-46 of Appendix B. On page B-44 are spectra of the RF emission from 0 to 1 gigahertz, as a function of the neutral background pressure of argon gas. As the pressure increases, the nonlinear mode coupling seems to increase, and gives rise to RF emission above 500 megahertz; finally, at very high pressures, the RF emission falls to very low levels. On page B-45 of Appendix B are spectra of the RF emission from argon gas over frequencies from 0 to 1 gigahertz, and for values of the background magnetic field which span a factor of 2 in magnetic field strength. The amplitude of the RF emission, and the degree of nonlinear mode coupling increased dramatically with magnetic field strength. This phenomenon was observed also on the modified Penning discharge operated for the ONR contract, and represents a somewhat surprising and counterintuitive result. It appears that the addition of a constraint to the system, in the form of an increasingly strong magnetic field, will increase the RF emission amplitudes, and promote the nonlinear processes which are responsible for coupling energy to higher frequencies.

During these exploratory investigations, RF detection equipment was used at frequencies of 10, 35, and 70 gigahertz. No emissions were observed under the operating conditions existing at the time. In addition, a panoramic spectrum analyzer which covers the range from 1 gigahertz to 28 gigahertz was borrowed from Professor Alexeff's AFOSR contract, and this instrument indicated no RF emission above 1 gigahertz, for the particular conditions observed. All of the detectors above 1 gigahertz, however, were relatively insensitive, (by a factor of about 20) compared with the antenna and detection system on our 0 to 1 gigahertz spectrum analyzer.

New Findings

In addition to the observations discussed above, subsequent exploratory research with the retarding potential energy analyzer revealed plasma floating potentials of several kilovolts, sometimes approaching the anode voltage, and characteristic ion energies of at least several hundred electron volts. RF emission spectra similar to those illustrated on pages B-44 and B-45, taken in argon gas, were found to produce an almost flat RF emission spectrum up to and beyond 1 gigahertz. A similar phenomenon was observed in the modified Penning discharge and is illustrated, for example, by the spectra on page B-30 of Appendix B. These flat, "white-noise" emission spectra are an extreme example of nonlinear mode coupling. The emission can be detected as low as 0.5 megahertz, at the low end of the AM broadcast band, where it interferes with reception on our laboratory radio. Such a broadband RF emitter may be useful in simulating the effects of broadband RF sources, or in jamming communications.

The classical Penning discharge plasma has been operated for a total duration of perhaps 40 hours, when it became necessary to completely disassemble the apparatus, make modifications to the electrodes, clean the walls of the glass vacuum vessel, and make modifications in the electrode position and geometry.

During routine operation of the classical Penning discharge, potentials as high as 10 kilovolts have been maintained along the magnetic field lines between the central anode, and the grounded cathode plates which are separated from the anode by approximately 30 centimeters. It is interesting that, in the presence of the plasma, average electric fields of at least 30 volts per centimeter are sustained along the magnetic field lines. Additional investigations are planned in the near future to measure the longitudinal electrostatic potential profile on the axis of the plasma, and do so in a way that will allow us to relate it to the effective plasma conductivity.

Publications Supported by AFOSR

During the 16 months since initiation of this contract, two publications/conference presentations were supported by it, and were so acknowledged. Abstracts of the publications which appeared in the conference proceedings are included in Appendix B, along with a copy of the poster materials presented at the meeting. We presented a paper at the 1982 IEEE International Conference on Plasma Science in Ottawa, Canada in which we described a paired comparison of the RF emissions from the classical Penning discharge, supported by the AFOSR contract, and the modified Penning discharge, operated in a magnetic mirror field, which was supported by the ONR contract. This paper contained preliminary results from the AFOSR experiment, taken shortly after it achieved its first plasma.

The second publication during the first 16 months of this contract consists of a four-page extended abstract and materials from the poster session which was presented at the International Conference on Plasma

Physics in Goteborg, Sweden on June 9-15, 1982. This paper is an expansion of that presented at the IEEE meeting in May, and contains additional experimental data relating to the paired comparison of high frequency RF emission from the two configurations of electric field dominated plasma.

INTERACTIONS WITH OTHER CONTRACT RESEARCH

The total external support of the UTK Plasma Science Laboratory during calendar year 1982 is shown on Table I below.

TABLE I

EXTERNAL SUPPORT OF UTK PLASMA SCIENCE LABORATORY

PRINCIPAL INVESTIGATOR	SOURCE	DURATION	EXPIRES	AMOUNT
I. Alexeff	NSF	3 years	Feb. '82	$100,000
I. Alexeff	AFOSR	2 years	Nov. '83	$260,000
J. R. Roth	ONR	57 months	Oct. '84	$249,651
J. R. Roth	AFOSR	2 years	Mar. '83	$ 96,278
Total Support, C.Y. 1982				$238,338

The bottom line shows the total financial support received from all sources during calendar year 1982, and the expiration dates shown are the expiration dates of the current contracts.

The ONR RF Emission Contract

The UTK Plasma Science Laboratory has been fortunate to have a small research contract, ONR N0014-80-C-0063, "Investigation of RF Emission from Electric Field Dominated Plasmas", which began on January 1, 1980, and has continued under Dr. Charles W. Roberson of the Naval Research Laboratory as program manager.

The experimental program supported by the ONR contract has produced a variety of interesting results, some of which it would not appropriate to pursue under the terms of the Navy contract, but some of which may relate to Air Force missions and interests, and/or to the research program for the AFOSR. Some of the latter topics could be addressed by either the AFOSR or ONR contract, depending on which apparatus provides the most fruitful opportunity at a given time.

There are some topics on which I intend to concentrate almost exclusively in the Navy supported research, and which would not be included in the proposed AFOSR contract work. In general, the ONR work would include experimental investigations of a basic research nature; which are exploratory of new physical phenomena in the plasma; which would apply mostly or exclusively to high mirror ratio, magnetospheric plasmas; which relate to low frequency communications; or which relate to the basic physics of the geometric mean emission process itself.

The research topics which would be done mostly or exclusively for the ONR contract would include the following:

1. Measurements need to be made to test the theoretically predicted dependence of the geometric mean emission frequency on ion mass. In the NASA Lewis work, the possible dependence of the emission frequency on ion mass was not suspected in the complete absence of a theory; the predicted $A^{-1/4}$ dependence should be easy to identify, since a modified Penning discharge can be operated with any gaseous species.

2. It would be desirable to determine the dependence of the emission characteristics on the degree of electron isotropy in velocity space. The theoretical analysis assumes counterflowing electron beams of equal number density, and it would be interesting to find out what degree of thermalization of the electron beams will result in failure to emit at the geometric mean frequency.

3. It would be desirable to observe the intensity of the RF emission as a function of the angle with respect to the magnetic field lines to determine, if possible, at what wave propagation angle the maximum growth rates occurs.

4. It would be desirable to observe the RF emission with an antenna capable of detecting polarization, and to determine the degree and nature of the RF polarization.

5. It would be desirable to insert pairs of probes in the plasma which would allow correlation studies to be made to determine the wave length and phase velocity of the unstable waves which are responsible for emitting at the geometric mean plasma frequency.

The AFOSR and ONR contracts with J. R. Roth as Principal Investigator are individual, distinct efforts, each with its own experimental apparatus and research assistants assigned to it. Some overlap occurs to the mutual benefit of both contracts, and includes sharing diagnostic instrumentation that otherwise might not be available, and sharing skills and experience among the research assistants. In connection with ONR contract, we brought on line several diagnostic instruments which are being used to take measurements on the AFOSR apparatus, shortly after we had our first plasma. These diagnostic instruments include a high voltage Langmuir probe, a retarding potential energy analyzer, a one-half meter Fastie-Ebert visible spectrometer, RF emission detection equipment, and other devices.

The AFOSR Sub-Millimeter Emission Contract

Prof. Igor Alexeff of the Electrical Engineering Department at UTK has been awarded a contract from AFOSR (# AFOSR 82-0045) for the development of a submillimeter emitter based on the "orbitron" configuration. We share the use of the UTK Plasma Science Laboratory, and have collaborated closely as co-authors on a number of recent papers. The AFOSR contracts of which we are Principal Investigators will interact synergestically to make possible more rapid progress than either one could independently. Already I have been able to loan Prof. Alexeff RF detectors and equipment which were used in some of his early work on the orbitron concept.

The AFOSR contract of Professor Alexeff is supporting research on the orbitron, a magnetic field free device for generating millimeter and submillimeter microwave radiation. This work is closely enough related to the RF emission work being funded by the AFOSR under J. R. Roth that a synergestic and productive exchange of ideas and diagnostic equipment occurs, but in no sense duplicates the efforts of Roth's AFOSR Contract.

Conference Presentations and Other Interactions

The interactions of this contract with the ONR contract at the UTK Plasma Science Laboratory and with the AFOSR contract 82-0045 under Prof. I. Alexeff has just been discussed. Experimental data from this contract first became available in late February 1982, and so the number of conference presentations and off-campus interactions to date has been limited. We also have wished to get an array of varied diagnostic instruments in place and in a position to take publishable data before saying too much about the quantitative aspects of our work.

Nonetheless, some of our preliminary exploratory investigations, described above, have made an interesting comparison against the modified Penning discharge operated for the ONR contract. We discussed a paired comparison of these qualitative features at the International Conference on Plasma Physics in Goteborg, Sweden, June 9-15, 1982. The abstracts and poster materials presented at this meeting are included in Appendix B of this report, and a trip report on interactions and disucssions are summarized in Appendix C.

These initial results also were discussed at the 1982 IEEE International Conference on Plasma Science, held in Ottawa, Canada, from May 17-19, 1982. An abstract of the paper presented at that meeting and the poster materials presented there is included in Appendix B. Appendix D of this report contains a trip report on that meeting which summarizes the discussions and technical sessions attended by the principal investigator which have a bearing on the subject matter of the AFOSR and ONR contracts.

While attending the Ottawa meeting, I had an opportunity to brief Dr. Charles W. Roberson, of the Naval Research Laboratory, on the progress of both the AFOSR and ONR contracts. He is the program manager for the ONR contract. Also at the Ottawa meeting, I had an opportunity to Brief Dr. Richard Gullickson, now assigned to the Pentagon, of our contract activities for AFOSR and ONR. At the Goteborg conference, in addition to the interactions documented in the trip report, I had an opportunity again to talk with Dr. Roberson of ONR and bring him up to date on our activities.

STAFFING

Principal Investigator

Dr. J. Reece Roth will continue to serve as Principal Investigator if this contract is renewed. Dr. Roth's resume is included in Appendix A. During the contract period, Dr. Roth's early work on the application of superconducting magnet facilities to plasma experiments, and his contributions to the study of plasma instabilities and turbulence were recognized by election to the grade of Fellow in the Institute of Electrical and Electronic Engineers. The support represented by this contract has made it possible for him to continue this work.

Dr. Roth obtained an S.B. in Physics from M.I.T. in 1959, and a Ph.D. from Cornell University in 1963 with a major in Engineering Physics. He joined the NASA Lewis Research Center in Cleveland, Ohio in 1963, where he was Principal Investigator ofthe Lewis Electric Field Bumpy Torus Project until 1978. He is presently on the faculty of the University of Tennessee, Knoxville, and is a Fellow of the IEEE.

In the past seventeen years, Dr. Roth has authored or co-authored 82 publications, of which 34 were articles in refereed journals, and the remainder 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 Mathematical Physics, Nature, and elsewhere. In addition to these publications, Dr. Roth has been author or co-author of 64 oral or poster presentations at professional society meetings, nearly all of which report experimental data on his scientific or engineering work.

Research Assistants

The first research assistant to join this contract was Mr. Robert L. Pastel who joined us at UTK for doctoral study on April 23, 1981, approximately 6 weeks after initiation of the contract. Mr. Pastel holds a Master's degree in Engineering Science and Mechanics from the University of Tennessee Space Institute, and a bachelor's degree in mathematics from the Virginia Polytechnic Institute. His home department is Engineering Science and Mechanics, and he returned to do further graduate work leading to the degree of Doctor of Philosophy. It is his intention to enter the field of high temperature plasma physics.

As a result of the delay in Mr. Pastel joining us, there was sufficient money in the first year budget to hire a temporary research assistant half-time from mid-June to mid-August. This assistant was a UT graduate with a bachelor's degree in Electrical Engineering who had a nearly 4.0 grade point average, Mr. Roger A. Richardson. Mr. Richardson was assigned the job of documenting, repairing, and placing into service the surplus 40 kilowatt dc power supply which powers the water-cooled Magnion coils required for this contract. Mr. Richardson did an excellent job. He repaired some defects which apparently escaped the previous users of the coil system by ORNL, and left it in perfect order when he left to assume a post at the Plasma Fusion Center at MIT, where he is pursuing graduate studies.

Upon renewal of the contract on March 15, 1982, and approval to increase the budget to a level that would allow the hiring two half-time research assistants, we hired Mr. Gregory J. Hutchens, an Engineering Physics student at UTK in his senior year. Mr. Hutchens has been assigned the task of developing and debugging a computer program that will make possible analysis ofthe retarding potential energy analyzer data. Mr. Hutchens was hired on the contract on April 1, 1982.

The fact that we have paid our research assistants on the average slightly less than was contemplated in the original budget has made it possible for us to hire an additional temporary half-time research assistant over the summer of 1982. This temporary research assistant on the AFOSR contract is Mr. Paul Spence, who holds a Master's degree from the Department of Engineering Science and Mechanics at UTK, and who also holds a bachelor's degree in physics from the Georgia Institute of Technology. He has a career interest in high temperature plasma physics and fusion energy.

Student Participation

Student involvement with the UTK Plasma Science Laboratory is shown on Table II. The eight half-time research assistants and the one quarter-time research assistant were supported by the contracts listed in Table I. The remaining students contributed significantly to progress in the lab, but did not cost these contracts anything since they were senior or graduate students who are doing projects for academic credit in the Plasma Lab.

Starting in the Fall Term of 1981 we have, I think, achieved a "critical mass" of plasma related students, and the UTK Plasma Science Laboratory is now an intellectually exciting place for both students and faculty who participate.

TABLE II

STUDENT INVOLVEMENT IN THE UTK PLASMA SCIENCE LABORATORY, 1982

Half-Time Research Assistants	8
Quarter-Time Research Assistants	1
Senior Projects	3
Undergraduate Special Projects Lab	1
Total Student Involvement	13

REFERENCES

1. Roth, J. R.; Alexeff, I.; and Mallavarpu, R.: New Mechanism for Electromagnetic Emission near the Geometric Mean Plasma Frequency. Phys. Rev. Lett., Vol. 43, No. 6, 445-449, August 6, 1979.

2. Alexeff, I.; Roth, J. R.; Birdwell, J. D.; and Mallavarpu, R.: Electromagnetic Emission and Anomalous Resistivity from Equal and Oppositely Directed Electron Beams. Physics of Fluids, Vol. 24, No. 7, 1348-1357 (1981).

3. Roth, J. R.: Modification of Penning Discharge Useful in Plasma Physics Experiments. RSI 37, No. 8, Aug. 1966, pp. 1100-1101.

4. Hayman, P. W.; and Roth, J. R.: RF Emission, Nonlinear Mode Coupling, and Ion Thermalization in a Modified Penning Discharge Plasma. APS Bulletin Vol. 26, p. 1061 (1981).

APPENDIX A

June 1982

PROFESSIONAL RESUME

J. Reece Roth
Department of Physics
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 was 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 the 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 plasmas, one with the ONR, the other with AFOSR. These

contracts provided half-time support for the Principal Investigator and 4 Research Assistants during 1982 and were worth about $110,000. In addition to research, taught a junior level course on plasma engineering, a graduate sequence on fusion technology, plasma diagnostics, and physics of fusion, and one-week minicourses on fusion energy and fusion diagnostics.

6. June 1982 to present. Research Professor, Department of Physics. Continuation of Contract Research, and teaching of graduate sequences in Fusion Energy and Plasma Physics.

IV. HONORS AND AWARDS

Relevant student honors include a four-year Sloan Scholarship at M.I.T., Presidency of the M.I.T. Rocket Research Society, and a Ford Fellowship at Cornell. 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," 17 Edition, 1980-81.

V. PROFESSIONAL SOCIETY MEMBERSHIPS

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

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. Member 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, 1970 to 1981.

APPENDIX B

PUBLICATIONS

ABSTRACT SUBMITTED FOR THE

1982 IEEE INTERNATIONAL CONFERENCE ON PLASMA SCIENCE

MAY 17-19, 1982

A PAIRED COMPARISON OF HIGH FREQUENCY RF EMISSION FROM TWO CONFIGURATIONS OF ELECTRIC FIELD DOMINATED PLASMA*

J. Reece Roth, P. W. Hayman, and R. L. Pastel
Department of Electrical Engineering
University of Tennessee
Knoxville, TN 37996-2100

We report paired comparison observations of RF emission from two electric field dominated plasmas over the range from 1.0 MHz to 70 GHz. One of these plasmas is a classical Penning discharge configuration with a plasma length of about 30 centimeters, a diameter of about 10 centimeters, and an approximately flat axial magnetic field of up to 0.4 Tesla. The second plasma (generated in a separate apparatus) is a modified Penning discharge operated in a magnetic mirror configuration with an axial mirror ratio of 5:1, intended to simulate magnetospheric plasmas. This plasma has approximately the same dimensions as the first, and maximum magnetic fields at the mirror throats of up to 0.4 Tesla. Both plasmas are electric field dominated in the sense of having strong radial and/or axial electric fields penetrating the plasma. Both are operated steady-state in helium and argon gas, and both are enclosed in glass vacuum systems which allow RF radiation to escape the plasma without forming a resonant cavity. The instrumentation available allows a continuous spectrum of RF emission up to 1 GHz to be displayed, and measurements to be made at isolated microwave frequency bands up to 70 GHz.

At the time of writing, no information is available on the RF emission characteristics of the classical Penning discharge. The RF emissions from the modified Penning discharge have recently been found to have several interesting characteristics. In addition to the previously reported[1,2] geometric mean emission frequency in the range from 10 to 40 MHz at background pressures below 2.4×10^{-4} Torr of Helium, we recently observed a low frequency peak, the fundamental of which is about 5 MHz, and which exhibits up to 30 or 50 harmonics before fading into the turbulent background. This peak occurs above 2.4×10^{-4} Torr, and the nonlinear mode coupling exhibited by its harmonic generation is sometimes visible up to 1 GHz. This "type II" emission appears to be related to rotating spokes driven by ExB/B² drift, which are a consequence of the diocotron instability.

The modified Penning discharge also exhibits RF emission at frequencies above 1 GHz, including the 1 cm band at 26 GHz at which the microwave interferometer operates. The origin and nature of these high frequency emissions are a matter for continuing study.

1.) I. Alexeff, J. R. Roth, J. D. Birdwell, and R. Mallavarpu: Electromagnetic Emission and Anomalous Resistivity from Equal and Oppositely Directed Electron Beams, Phys. Fluids Vol. 24, No. 7 (1981) pp. 13[illegible]-57.
2.) P. W. Hayman and J. R. Roth: RF Emission, Nonlinear Mode Coupling, and Ion Thermalization in a Modified Penning Discharge Plasma, APS Bulletin Vol. 26, No. 7 (1981) p. 1061.

* The work on the classical Penning discharge was supported by AFOSR contract #81-0093, and the work on the modified Penning discharge by ONR contract #N0014-[illegible]-C-[illegible]3.

For Reference Citation: J. Reece Roth, Paul W. Hayman, and R. L. Pastel, Paper 3E1, Proceedings of the 1982 IEEE International Conference on Plasma Science, IEEE Catalog No. 82CH1770-7, p. 65.

PAPER 3E-1

A PAIRED COMPARISON OF HIGH FREQUENCY RF EMISSION FROM TWO CONFIGURATIONS OF ELECTRICAL FIELD DOMINATED PLASMA*

J. REECE ROTH, PAUL W. HAYMAN, AND ROBERT L. PASTEL

DEPARTMENT OF ELECTRICAL ENGINEERING

UNIVERSITY OF TENNESSEE

KNOXVILLE, TENNESSEE 37996-2100

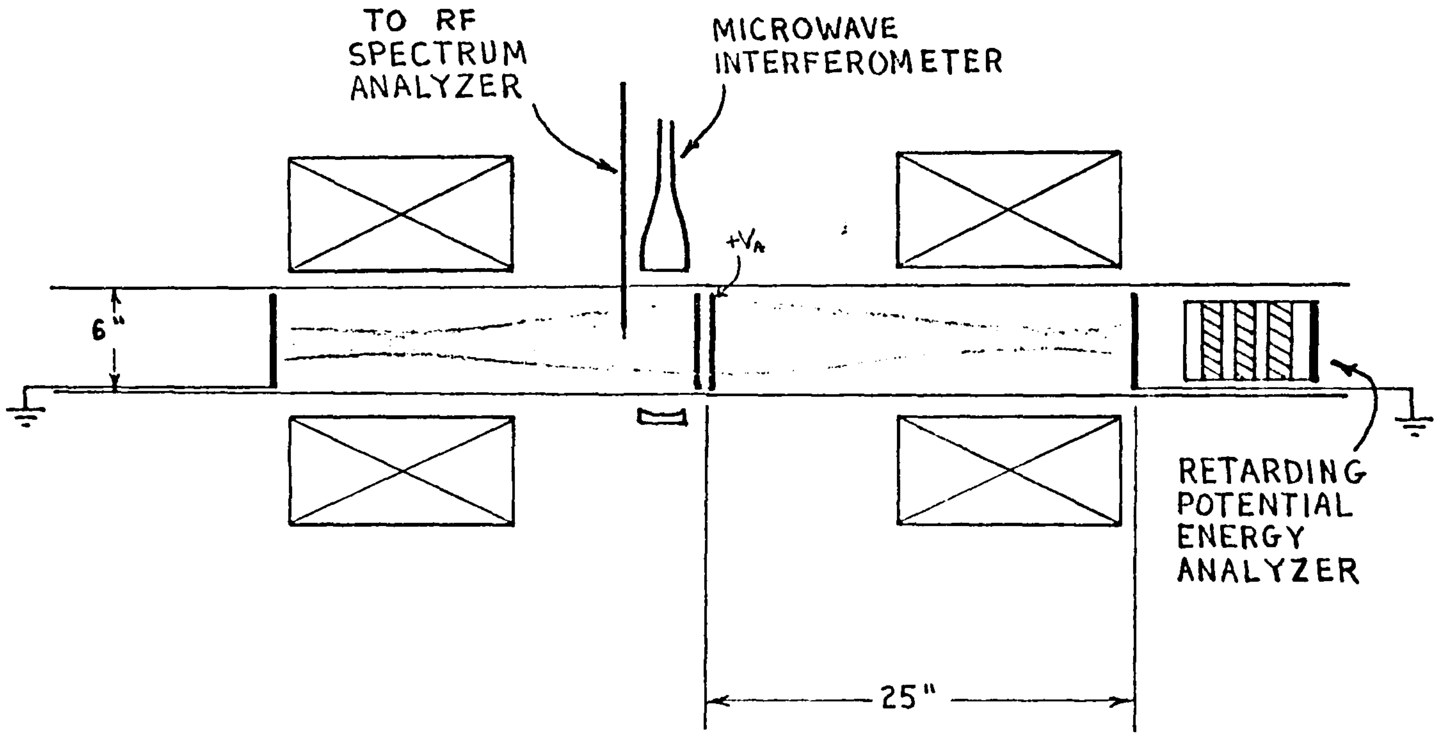
1982 IEEE INTERNATIONAL CONFERENCE ON PLASMA SCIENCE

MAY 17-19, 1982

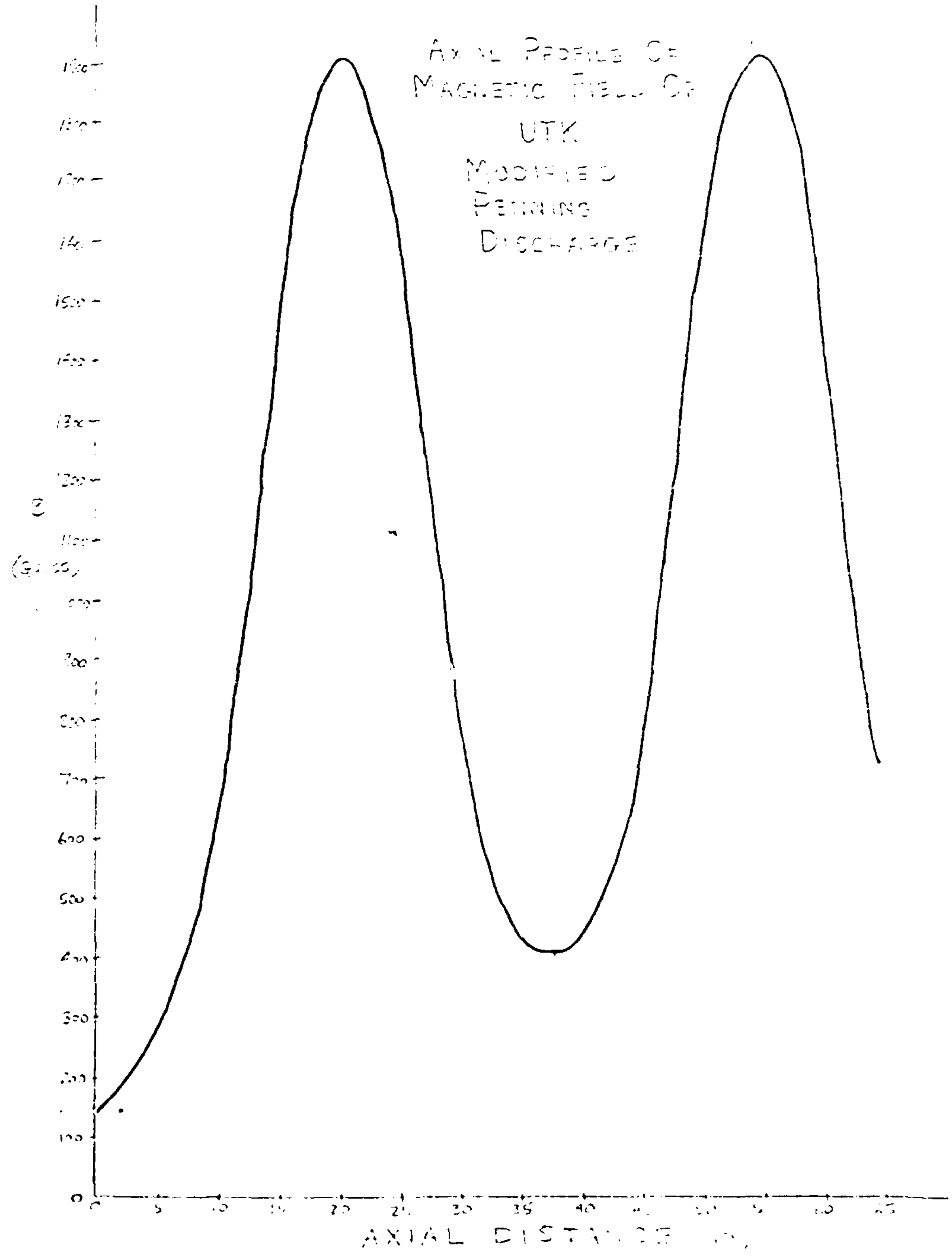
OTTAWA, CANADA

* The work on the classical Penning discharge was supported by AFOSR contract #81-0093, and the work on the modified Penning discharge by ONR contract #N00014-80-C-0063.

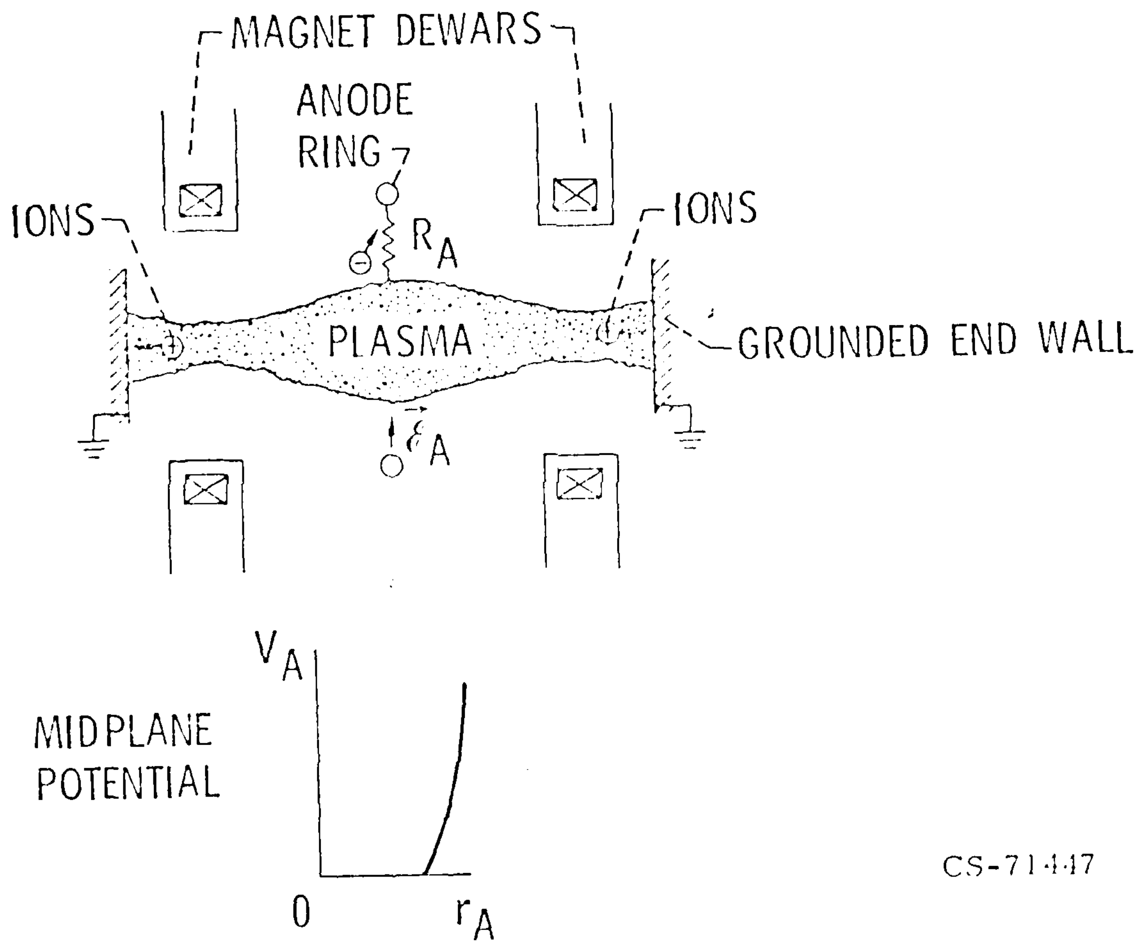
For Reference Citation: J. Reece Roth, Paul W. Hayman, and R. L. Pastel, Paper 3E1, Proceedings of the 1982 IEEE International Conference on Plasma Science, IEEE Catalog No. 82CH1770-7, p. 65.



MODIFIED PENNING
DISCHARGE


AXIAL PROFILE OF
MAGNETIC FIELD OF
UTK
MODIFIED
PENNING
DISCHARGE
AXIAL DISTANCE

EQUIVALENT CIRCUIT OF MODIFIED PENNING DISCHARGE



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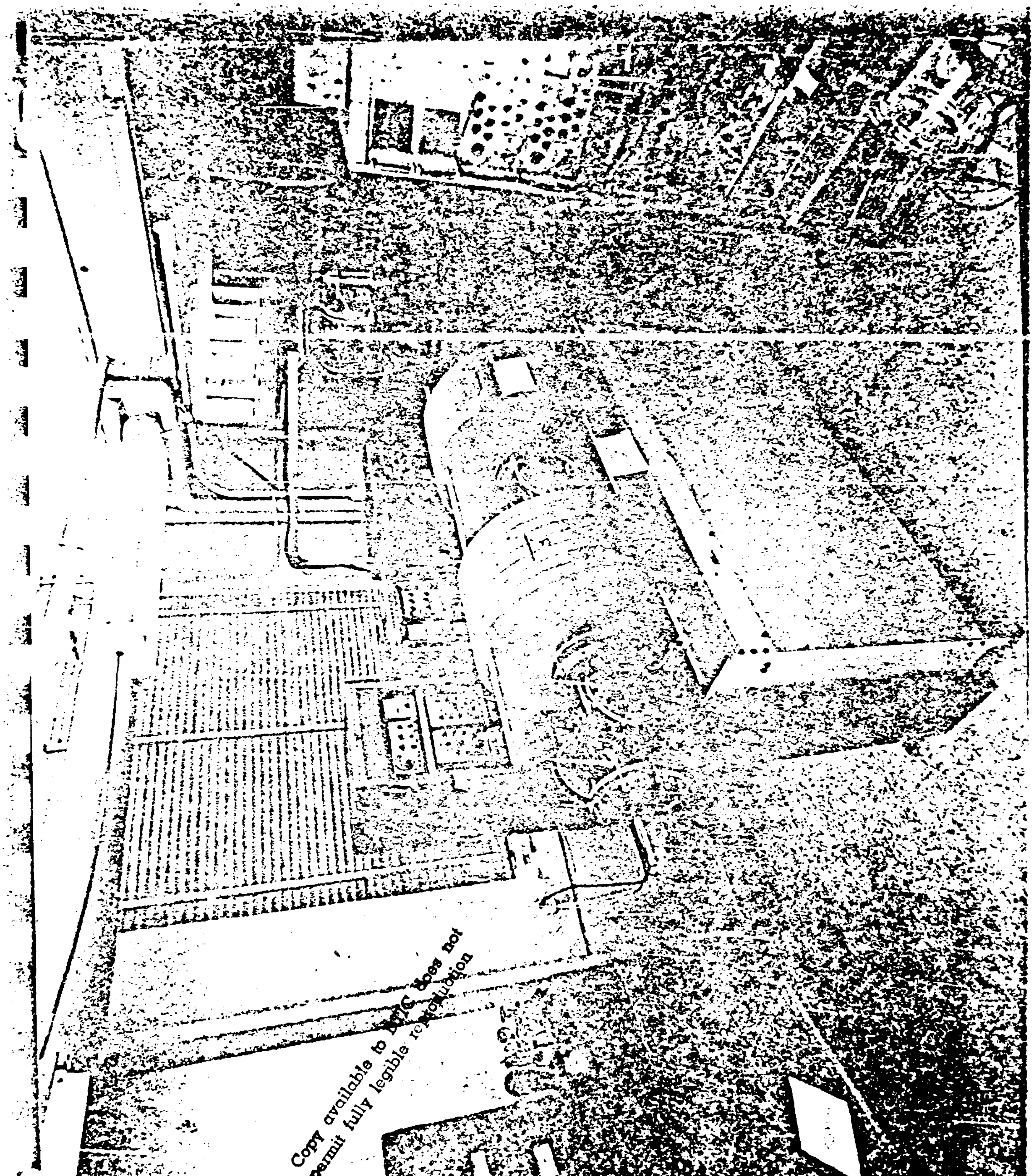

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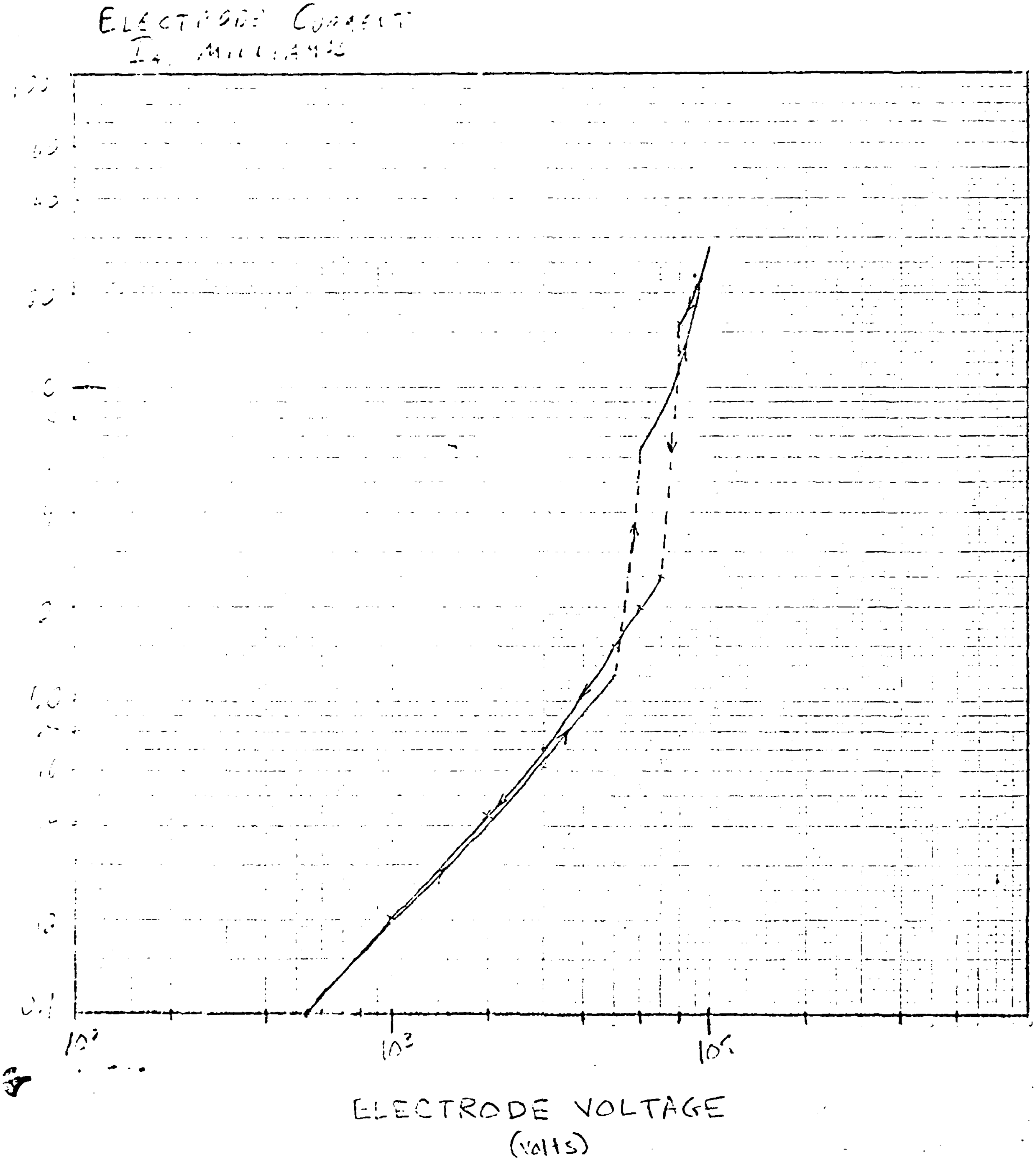
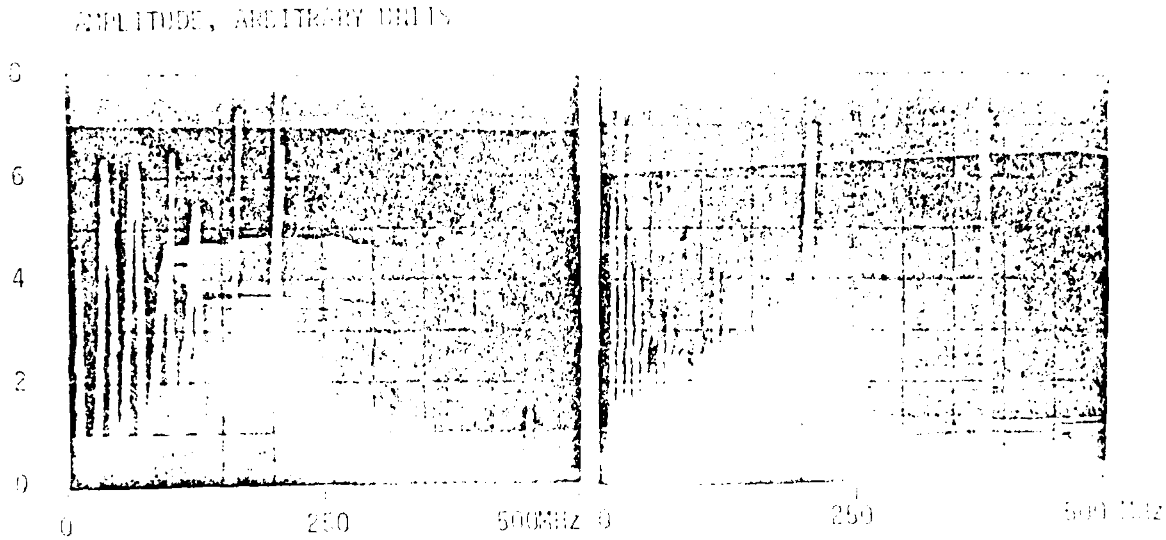


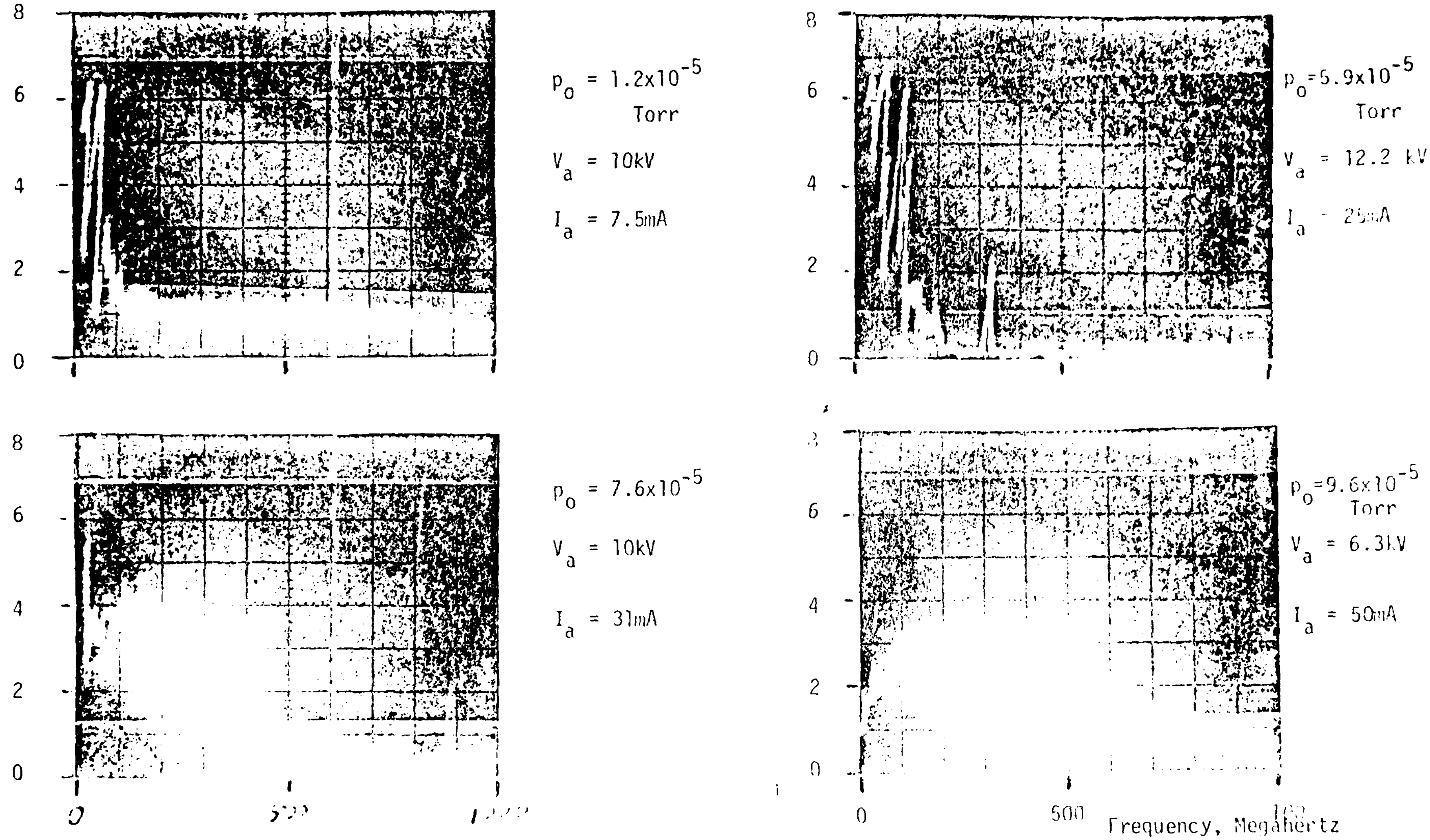
EMISSIONS FROM MODIFIED PENNING DISCHARGE



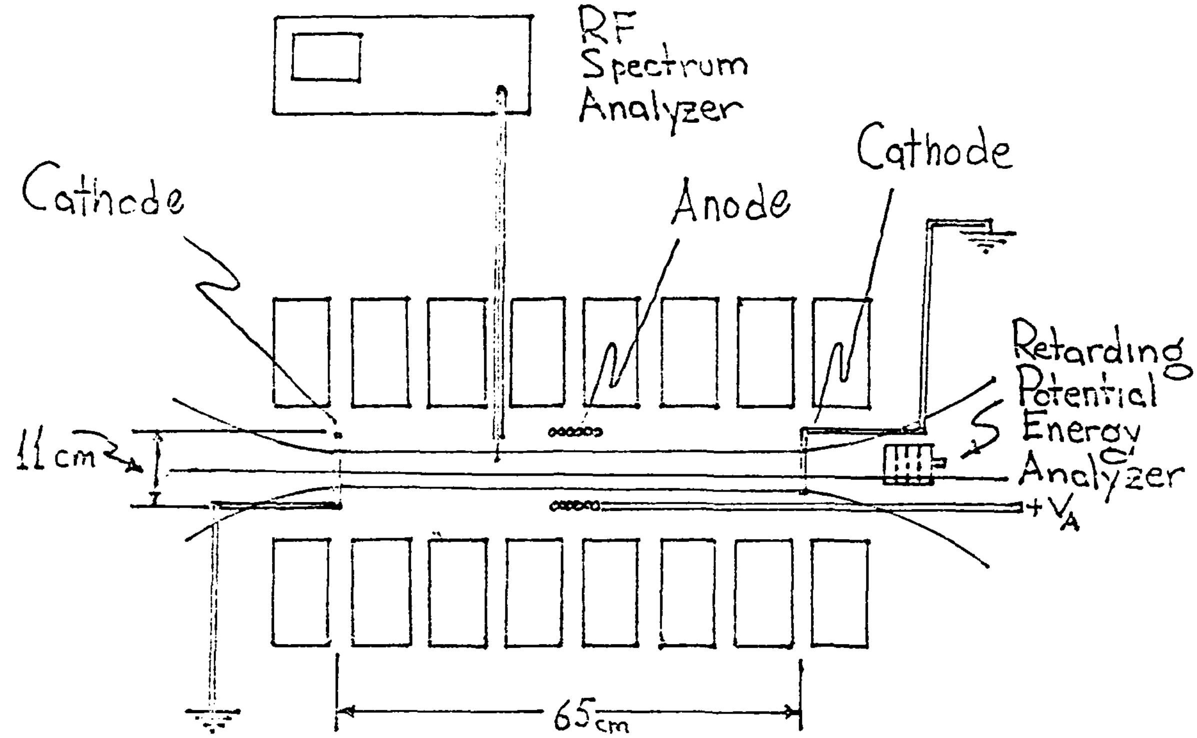
Spectrum of near-field emissions from the modified Penning discharge operating with helium gas at a 5:1 mirror ratio with B_{max} = 0.38 Tesla.

A) Mode I operation at $p_0 = 7.0 \times 10^{-5}$ Torr, electrode voltage V_a = 4.0 kV, and electrode current I_a = 4.0 mA. B) Mode II operation at $p_0 = 4.0 \times 10^{-4}$ Torr, $n_e = 9.1 \times 10^{9}/cm^3$, V_a = 2.0 kV, and I_a = 46 mA.

MOFIDIED PENNING DISCHARGE

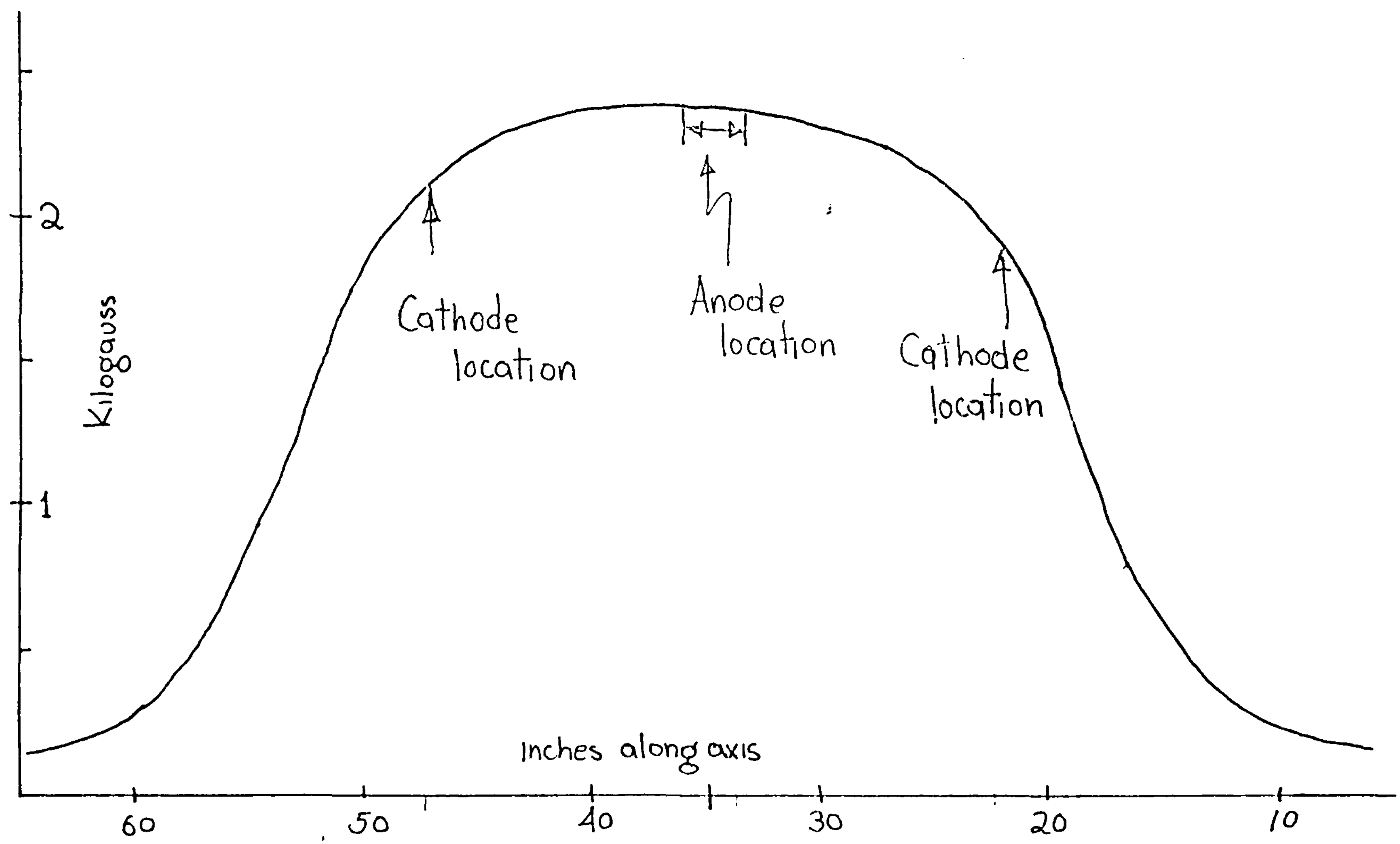


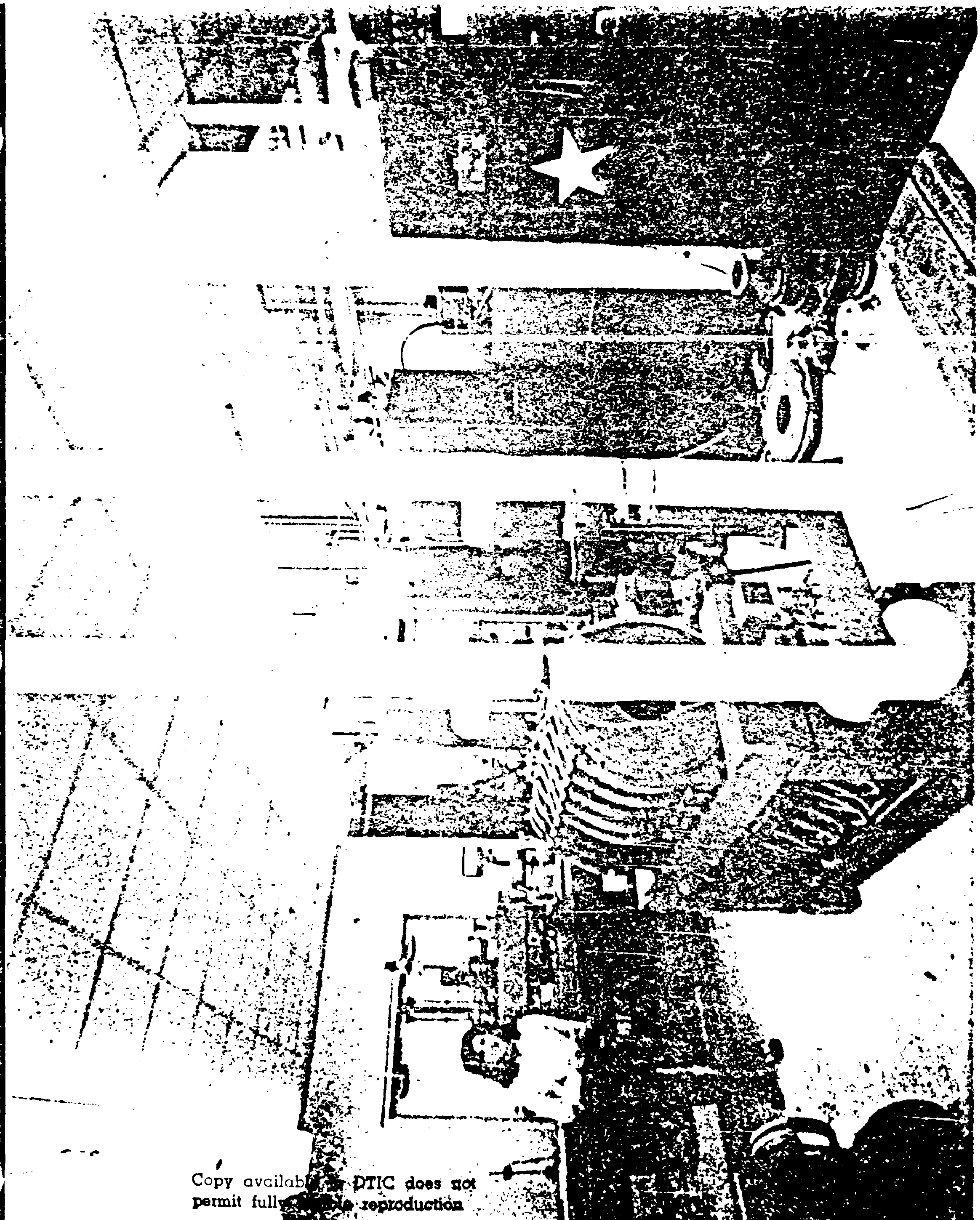
Spectrum of near-field emissions from the modified Penning Discharge operating in Argon gas at a 5:1 mirror ratio with B_{max} = 0.38 Tesla.

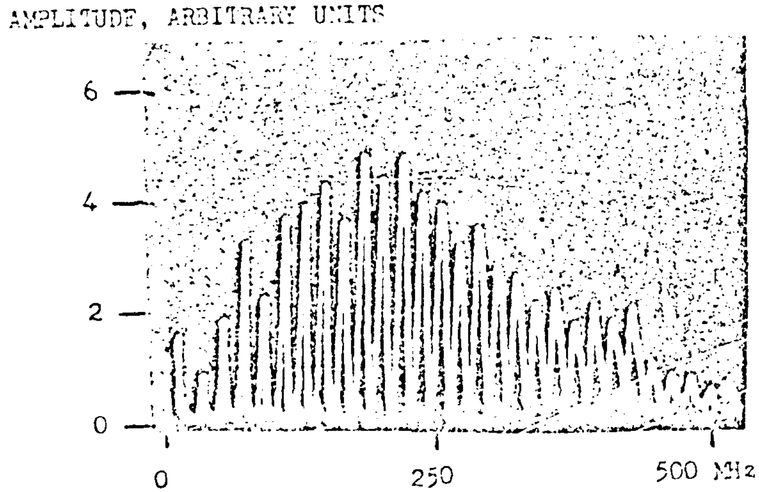


CLASSICAL
PENNING DISCHARGE

Axial Magnetic Field Profile of Penning Discharge

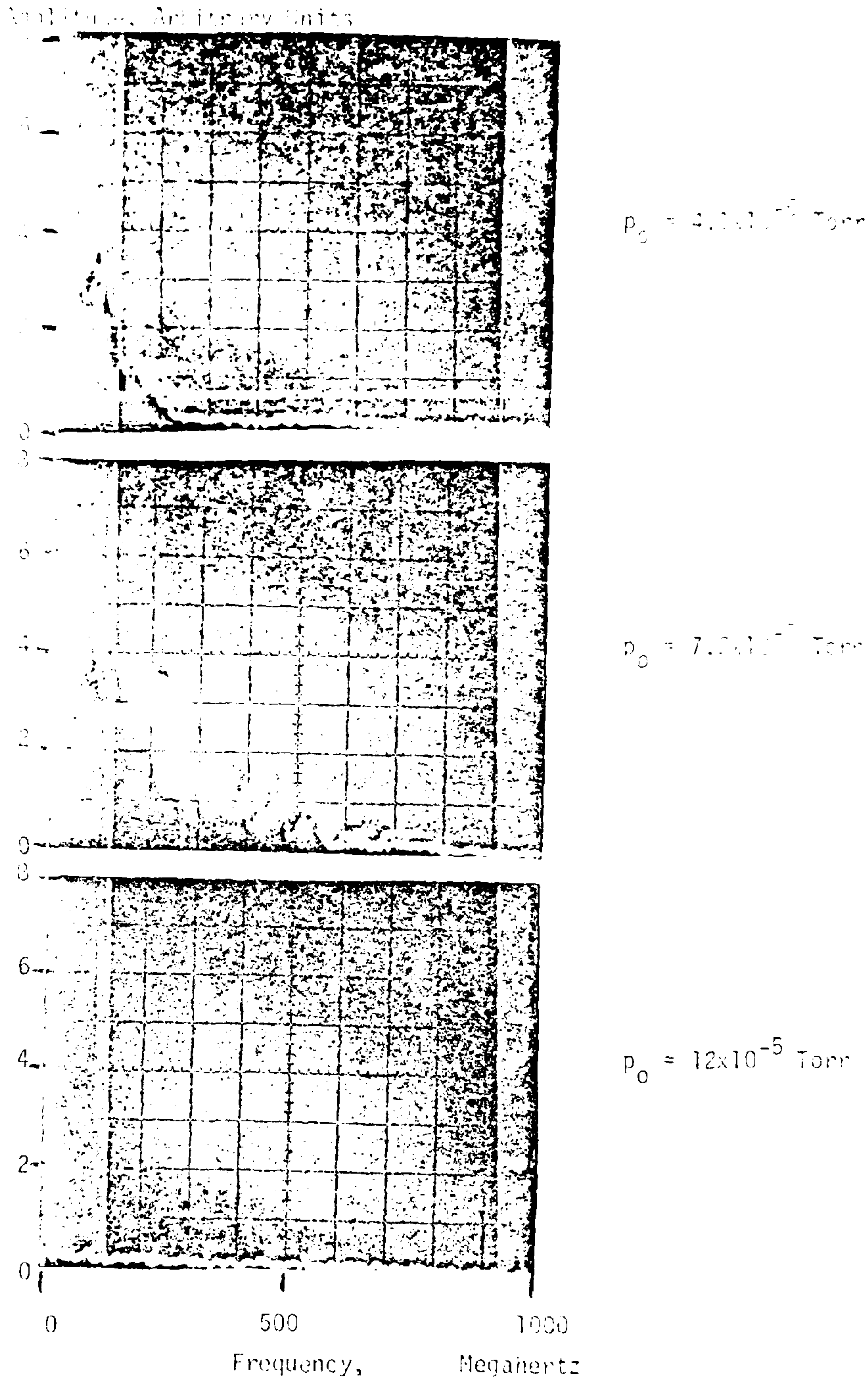




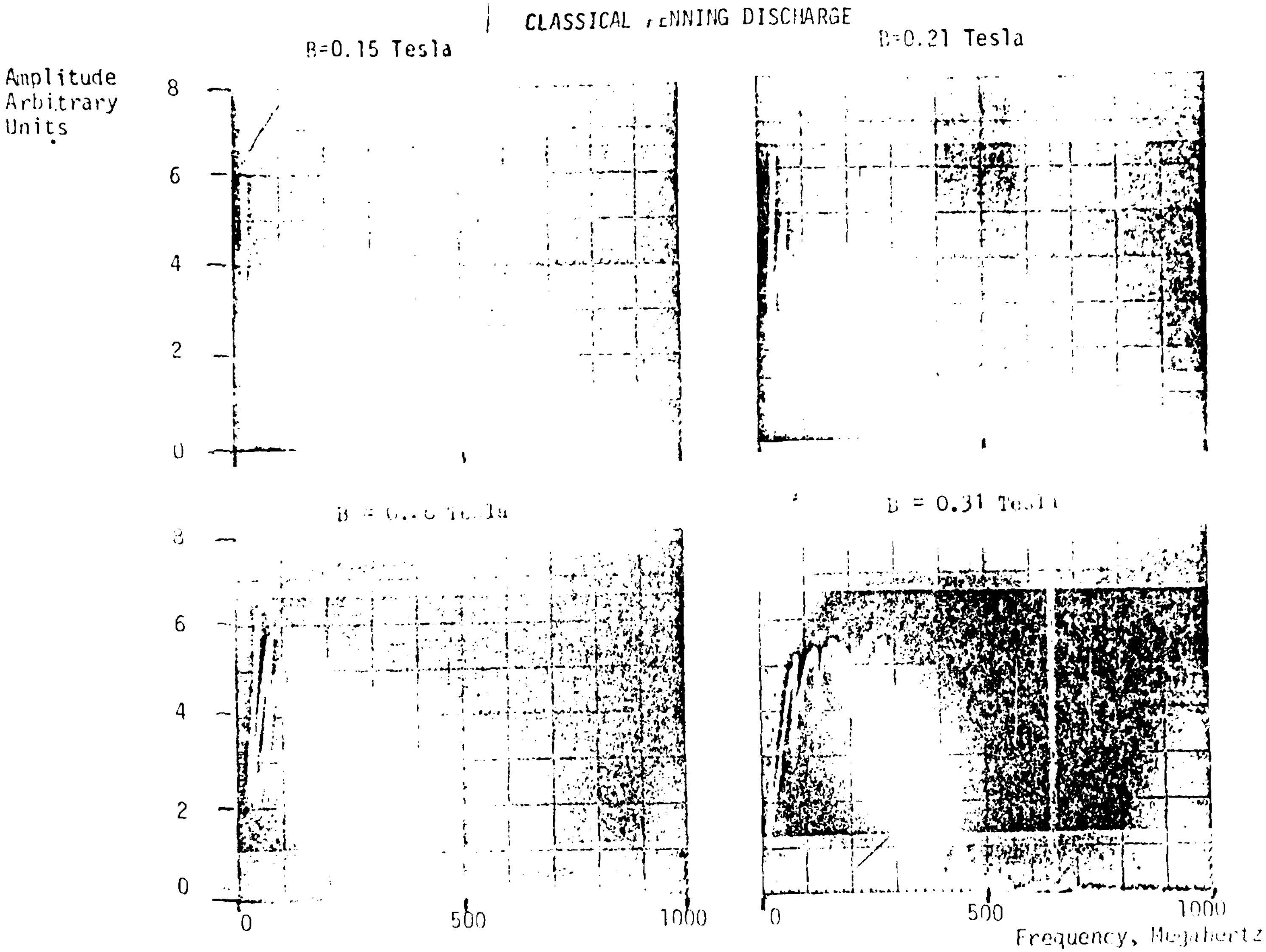


Spectrum of near field emissions from the classical Penning discharge with uniform magnetic field of $B = 0.285$ Tesla, $p_0 = 2.3 \times 10^{-4}$ Torr of argon gas, electrode voltage $V_a = 1.1$ kV, and electrode current $I_a = 31$ mA.

... PENNING DISCHARGE



Spectrum of near-field emissions from the classical Penning Discharge operating with Argon gas and a magnetic field B = 0.24 Tesla.



Spectrum of near-field emissions in Argon gas for D.C. electrode voltage V_a=6.5 kV, background pressure p_o = $6x10^{-5}$ Torr.

PREPRINT
Presented at the International Conference on Plasma Physics
Goteborg, Sweden, June 9-15, 1982

B-16

A PAIRED COMPARISON OF HIGH FREQUENCY RF EMISSION FROM TWO CONFIGURATIONS OF ELECTRIC FIELD DOMINATED PLASMA

J. Reece Roth, Paul W. Hayman, and Robert L. Pastel
Department of Electrical Engineering
University of Tennessee
Knoxville, Tennessee, U.S.A. 37996-2100

Abstract: We report paired comparison observations of RF emission from two steady-state electric field dominated plasmas, a classical Penning discharge operating in an axially uniform magnetic field, and a modified Penning discharge operating in an axisymmetric magnetic mirror. Measurements were made at frequencies up to 70 GHz. Much RF activity was observed below 1.0 GHz.

1. Introduction

Radio Frequency (RF) emissions from plasmas can yield diagnostic information about the electron number density (from emissions at the electron plasma frequency), and the ionic species (from emissions at the ion plasma frequency); about turbulence and nonlinear mode coupling in the plasma; and about physical processes in the plasma such as rotating spokes arising from the E/B driven diocotron instability and/or low frequency MHD instabilities. Such near-field emission phenomena are best observed in steady-state electric field dominated plasmas where conventional RF spectral analysis equipment has enough time to operate (as opposed to pulsed experiments lasting less than one second), and which have a substantial energy input through axial and transverse electric fields which penetrate the plasma. Such plasmas are generated by the classical (ref. 1) and modified (ref. 2) Penning discharges. These are known to be penetrated by strong radial and axial electric fields, up to kilovolts per centimeter, to operate with high levels of electrostatic turbulence, to heat ions by an E/B drift mechanism, and to emit RF radiation in the near field over a wide range of frequencies (refs. 3-6). In this paper we report a paired

For Reference Citation: J. R. Roth, P. W. Hayman, and R. L. Pastel, Paper 11p-II-02, Proceedings of the 1982 International Conference on Plasma Physics, Goteborg, Sweden, June 9-15, 1982, p. 250.

comparison of RF emissions from a classical Penning discharge, (with the plasma in a uniform magnetic field), with emissions from a modified Penning discharge which is operated in a magnetic mirror.

2. The Modified Penning Discharge

The modified Penning discharge (ref. 2) is operated in a 5:1 magnetic mirror ratio configuration which is intended to simulate the high mirror ratios of magnetospheric plasmas. The plasma is approximately 10 cm in diameter at the midplane, one meter in length, and has a maximum magnetic field up to 0.4 Tesla at the mirror throat. A schematic of the modified Penning discharge is shown in Figure 1. The plasma was operated with helium and argon gas, and is

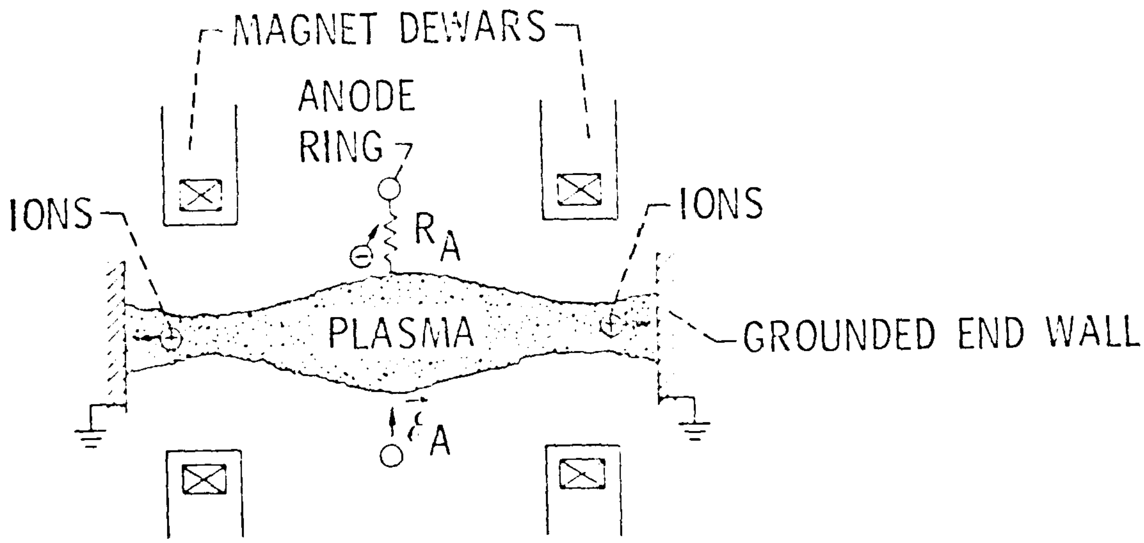


Figure 1. Schematic of the modified Penning discharge.

enclosed in a glass vacuum system which allows RF radiation to escape.

This modified Penning discharge produced two modes of RF emission, as shown in Figure 2. The low pressure mode (Mode I) shown on Fig. 2A is apparently a manifestation of the geometric mean emission frequency (Ref. 5) and harmonics out to about 500 MHz. The high pressure mode (Mode II) on Fig. 2B appears to be a manifestation of diocotron-like spokes rotating with the E/B drift velocity, with as many as 30 harmonics, sometimes visible to 500 MHz.

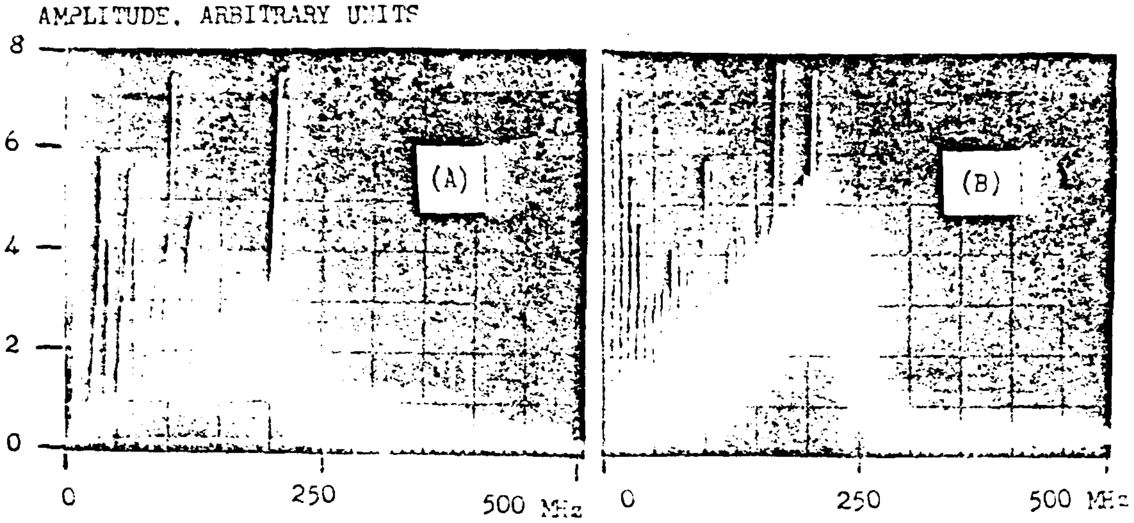


Figure 2. Spectrum of near-field emissions from the modified Penning discharge operating with helium gas at a 5:1 mirror ratio with B_{max} = 0.38 Tesla. A) Mode I operation at p_0 = 4.4 x 10^{-3} Torr, electrode voltage V_a = 4.0 kV, and electrode current I_a = 3.0 mA. B) Mode II operation at p_0 = 2.3 x 10^{-4} Torr, n_e = 7.6 x 10^{8}/cm^3, V_a = 2.0 kV, and I_a = 46 mA.

3. The Classical Penning Discharge

The classical Penning discharge (ref. 1) was operated with a uniform magnetic field up to 0.43 Tesla, and produced a plasma about 10 cm in diameter and one meter long. The plasma was operated in the steady state with helium and argon gas, and a glass vacuum system allowed RF radiation to escape. A preliminary spectrum of RF emission from 0 to 500 MHz is shown on Fig. 3. This plasma appears to operate in only a single mode, and to produce spectra of which Figure 3 is characteristic for both helium and argon gas. The example shown has 27 harmonics extending out to 500 MHz, and harmonics have been observed to 1.0 GHz. Many nonlinear mode coupling phenomena are apparent, including an example of plasma "lability" in which the spectral amplitude is greatest around the 8th harmonic at 200 MHz. The fundamental appears to be an example of the geometric mean emission frequency (ref. 5). RF detection equipment was used at frequencies of 10, 35, and 70 GHz, and no emissions were observed under the existing conditions.

Figure 3. Spectrum of near field emissions from the classical Penning discharge with uniform magnetic field of B = 0.285 Tesla, $p_0 = 2.3 \times 10^{-4}$ Torr of argon gas, electrode voltage V_a = 2.1 kV, and electrode current I_a = 31 mA.

Acknowledgements: The classical Penning discharge investigations were supported by AFOSR contract #81-0093, and the modified Penning discharge research by ONR contract #N00014-80-C-0063

References:

1. Penning, F. M.; and Nienhuis, K.: Construction and Application of a New Design of the Philips Vacuum Gauge. Philips Technical Review 11, No. 4 (1949), pp. 116-122.

2. Roth, J. R.: Modification of Penning Discharge Useful in Plasma Physics Experiments. RSI 37, No. 8 (1966), pp. 1100-1101.

3. Roth, J. R.: Experimental Study of Spectral Index, Mode Coupling, and Energy Cascading in a Turbulent, Hot-Ion Plasma. Phys. of Fluids 14, No. 10. (1971), pp. 2193-2202.

4. Kambic G. X.: Determination of the Radial Potential Profile in the Modified Penning Discharge with a Heavy Ion Beam Probe. IEEE Trans. on Plasma Science, Vol. PS-4, No. 1 (1976), pp. 1-5.

5. Alexeff, I.; Roth, J. R.; Birdwell, J. D.; and Mallavarpu, R.: Electromagnetic Emission and Anomalous Resistivity from Equal and Oppositely Directed Electron Beams. Physics of Fluids 24, No. 7 (1981), pp 1348-1357.

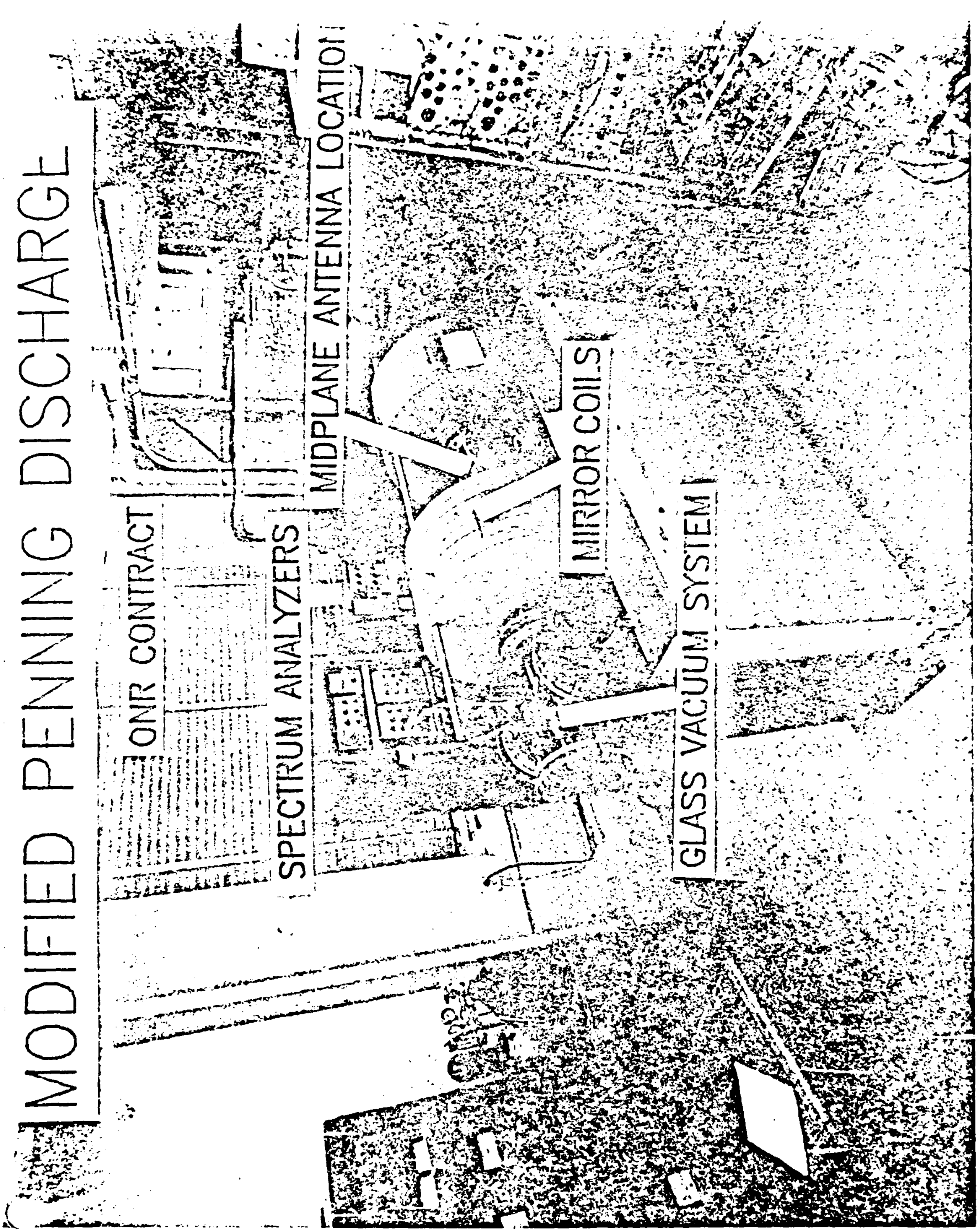
6. Roth, J. R. and Gerdin, G. A.: Characteristics of the NASA Lewis Bumpy Torus Plasma Generated with High Positive or Negative Applied Potentials. Plasma Physics 19, No. 5 (1977), pp. 423-446.

A PAIRED COMPARISON OF HIGH FREQUENCY RF EMISSION FROM TWO CONFIGURATIONS OF ELECTRIC FIELD DOMINATED PLASMA*

J. REECE ROTH, PAUL W. HAYMAN, AND ROBERT L. PASTEL

DEPARTMENT OF ELECTRICAL ENGINEERING
UNIVERSITY OF TENNESSEE
KNOXVILLE, TENNESSEE 37996–2100

*The work on the classical Penning discharge was supported by AFOSR contract #81–0093, and the work on the modified Penning discharge by ONR contract #N00014–80–C–0063.


MODIFIED PENNING DISCHARGE
ONR CONTRACT
SPECTRUM ANALYZERS
MIDPLANE ANTENNA LOCATION
MIRROR COILS
GLASS VACUUM SYSTEM

THE MODIFIED PENNING DISCHARGE

CONSISTS OF A STEADY–STATE PENNING DISCHARGE IN A 5:1 MAGNETIC MIRROR FIELD.

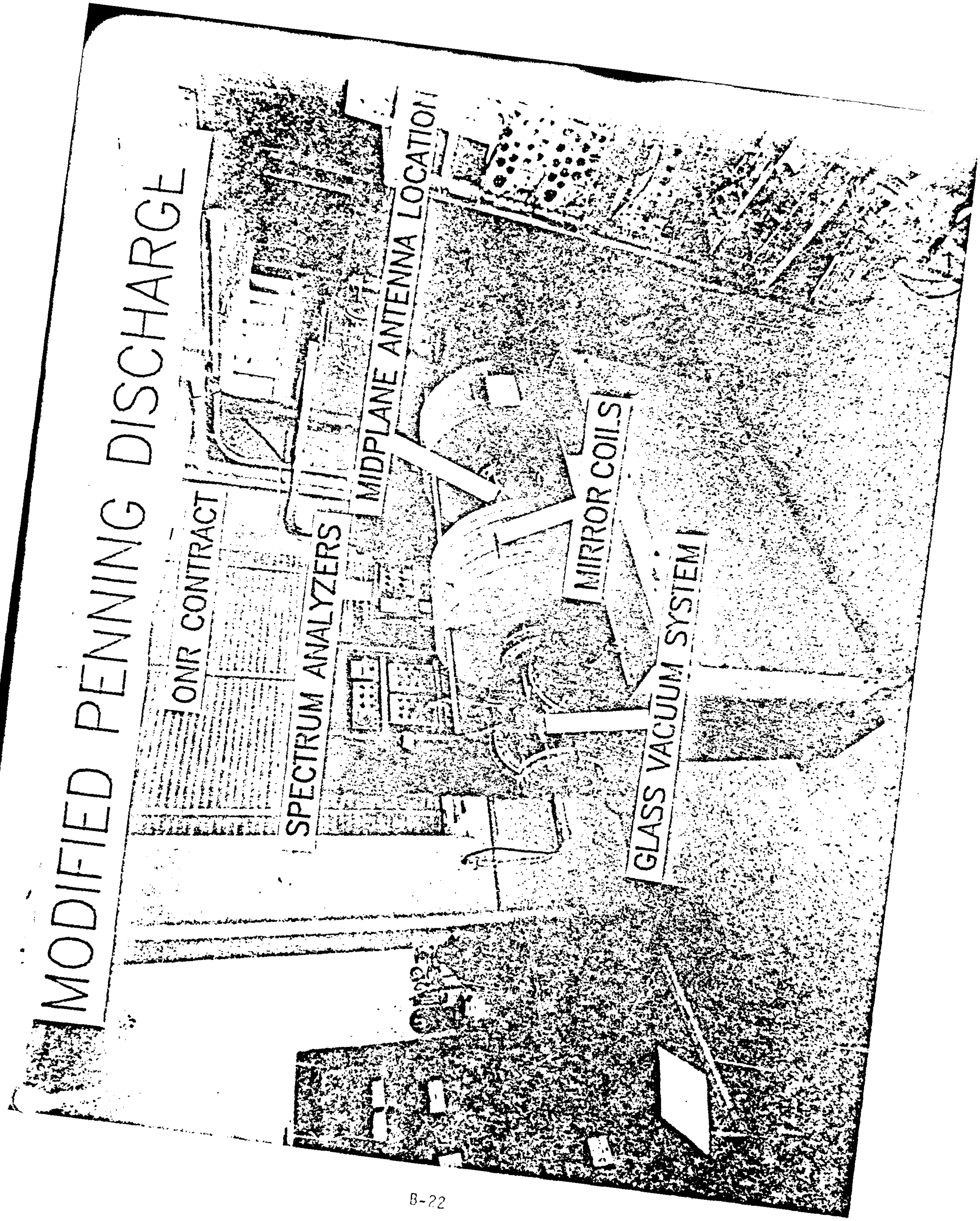
HAS STRONG (ABOUT 100 VOLT/cm) ELECTRIC FIELDS PARALLEL TO THE MAGNETIC FIELD.

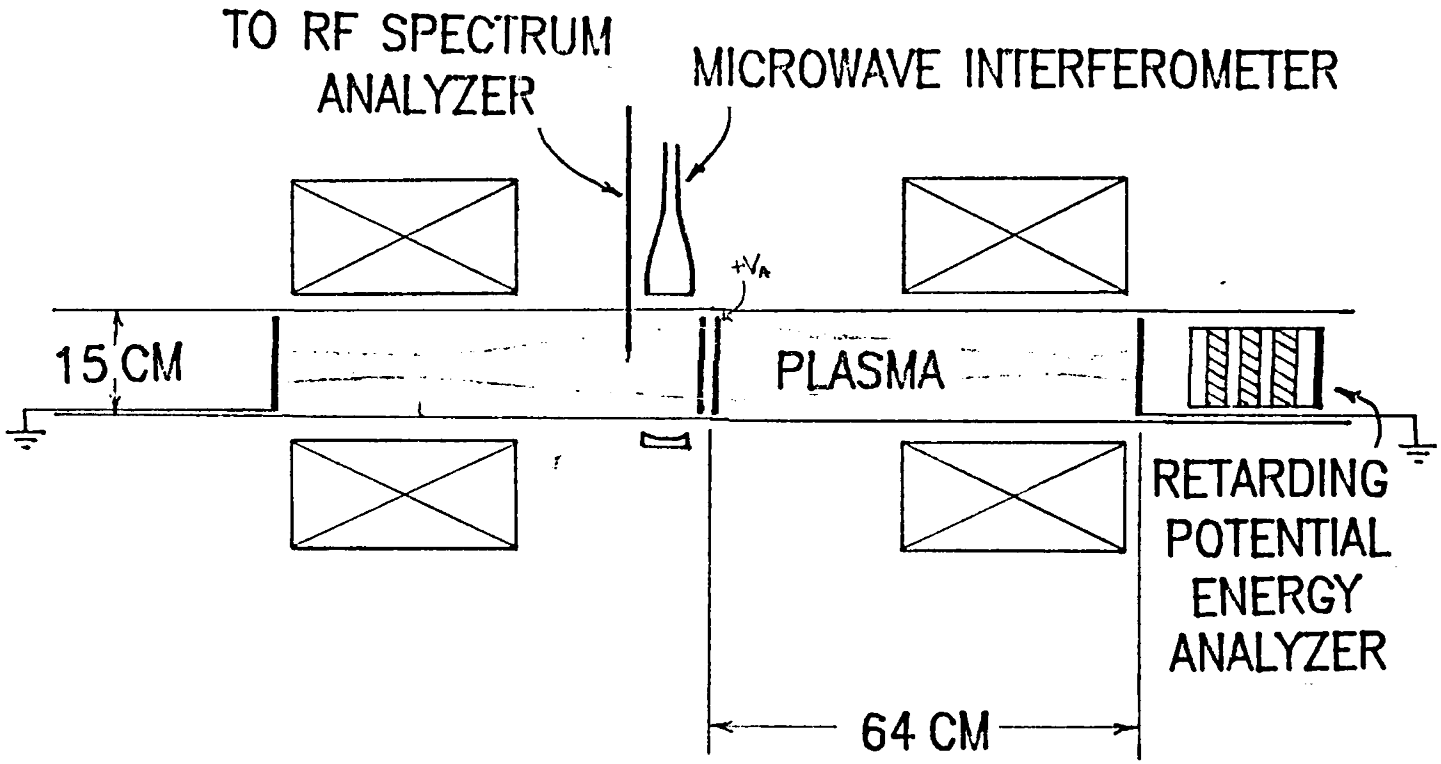
PRODUCES IONS WITH KILOVOLT LONGITUDINAL ENERGIES AS MEASURED WITH A RETARDING POTENTIAL ENERGY ANALYZER.

OPERATES IN TWO MODES, SEPARATED BY A DISCONTINUITY IN THE I–V PLANE.

IN ARGON GAS, EXHIBITS A FLAT SPECTRUM OF RF EMISSION FROM 0.5 MHz TO 1 GHz.

DISPLAYS MUCH NONLINEAR MODE COUPLING AMONG HARMONICS OF THE ELECTRON PLASMA FREQUENCY AND THE GEOMETRIC MEAN EMISSION FREQUENCY.


MODIFIED PENNING DISCHARGE
ONR CONTRACT
SPECTRUM ANALYZERS
MIDPLANE ANTENNA LOCATION
MIRROR COILS
GLASS VACUUM SYSTEM



MODIFIED PENNING DISCHARGE

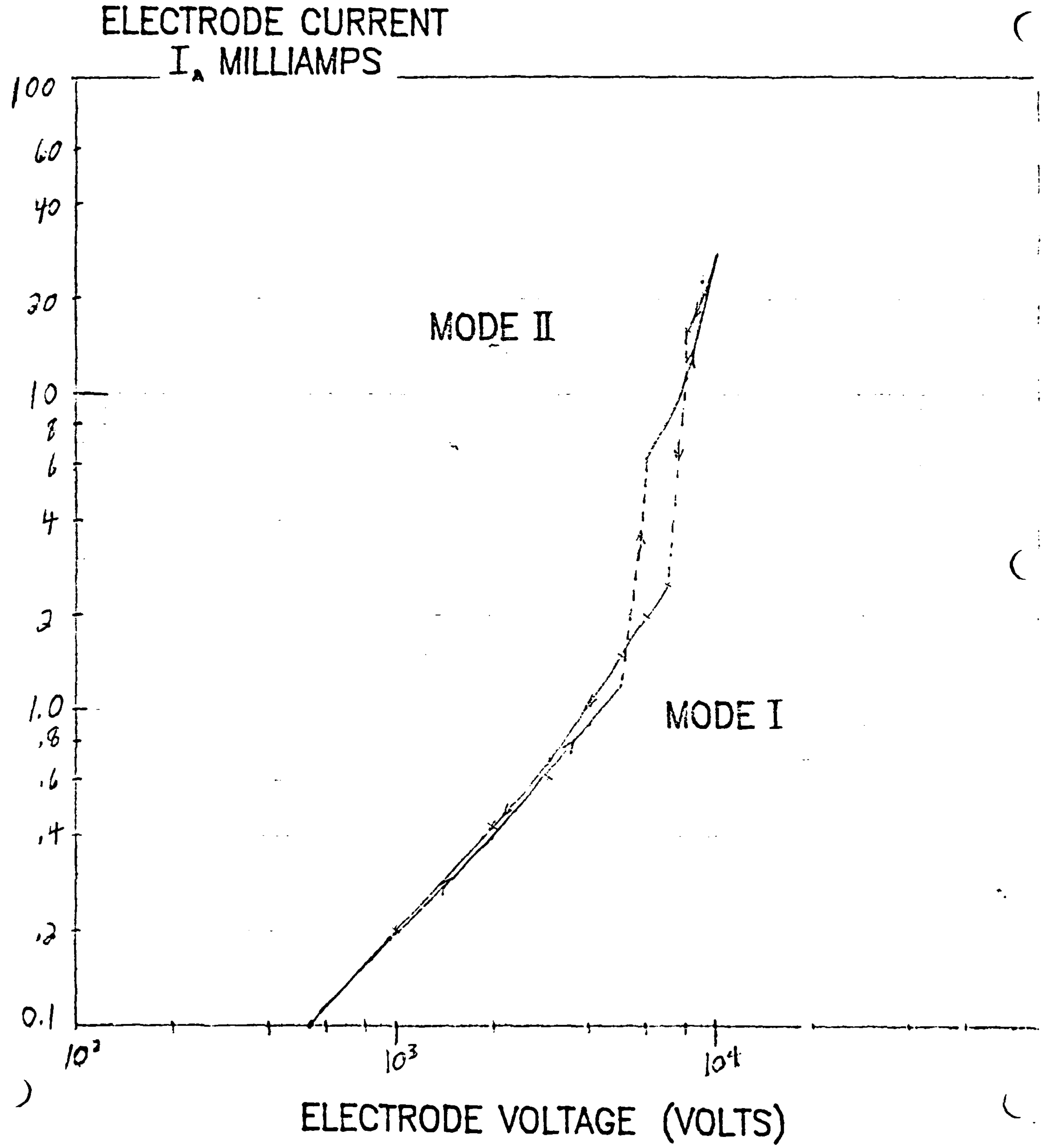
CURRENT–VOLTAGE CURVE
OF
THE MODIFIED PENNING DISCHARGE

NOTE HYSTERESIS AND DISCONTINUOUS TRANSITION BETWEEN MODES.

THE NUMBER DENSITY OF MODE I IS BELOW $10^8/CM^3$.

THE NUMBER DENSITY OF MODE II IS ABOUT $1-5 \times 10^9/CM^3$.

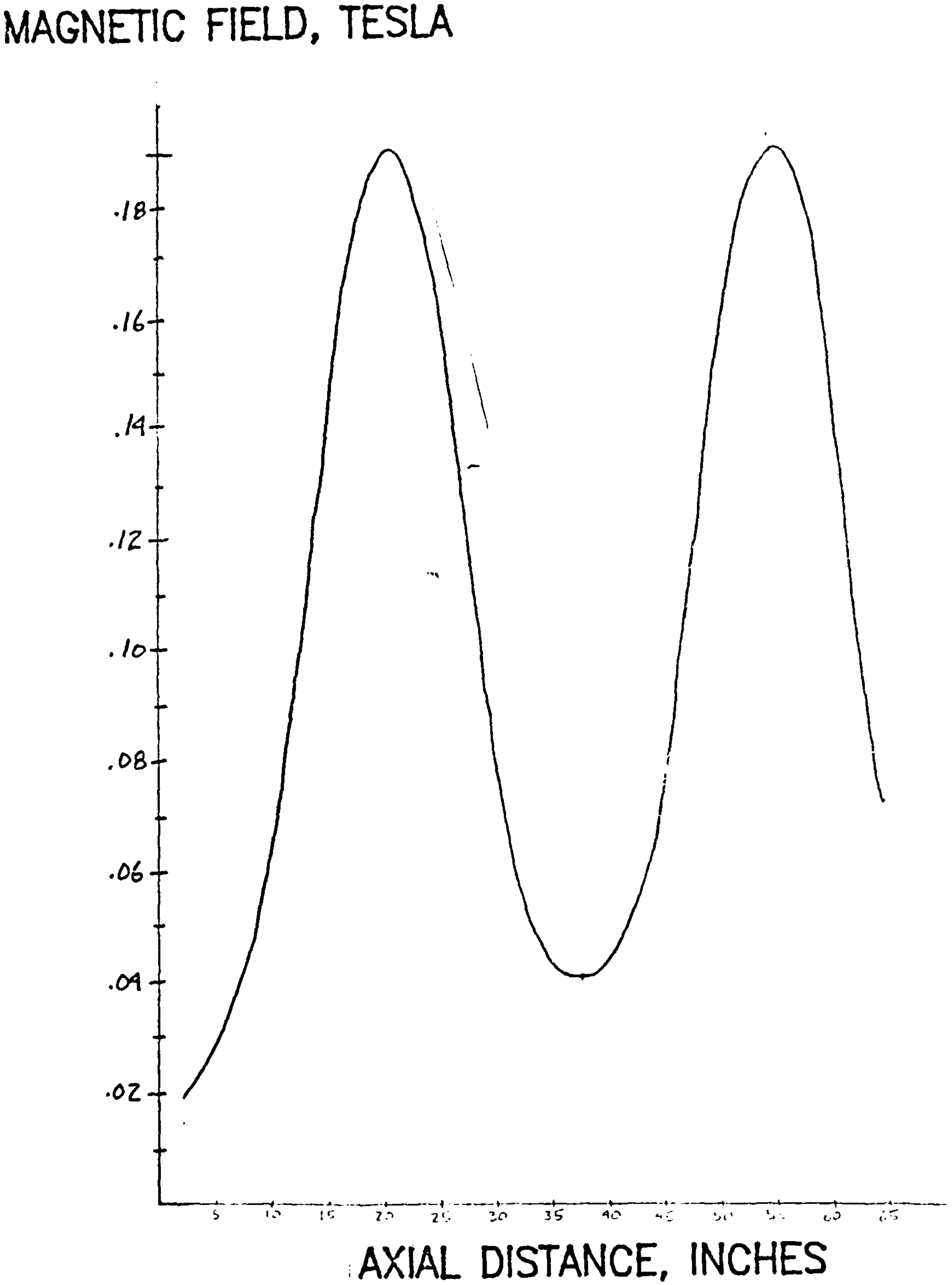
MODIFIED PENNING DISCHARGE



AXIAL MAGNETIC FIELD PROFILE OF UTK MODIFIED PENNING DISCHARGE

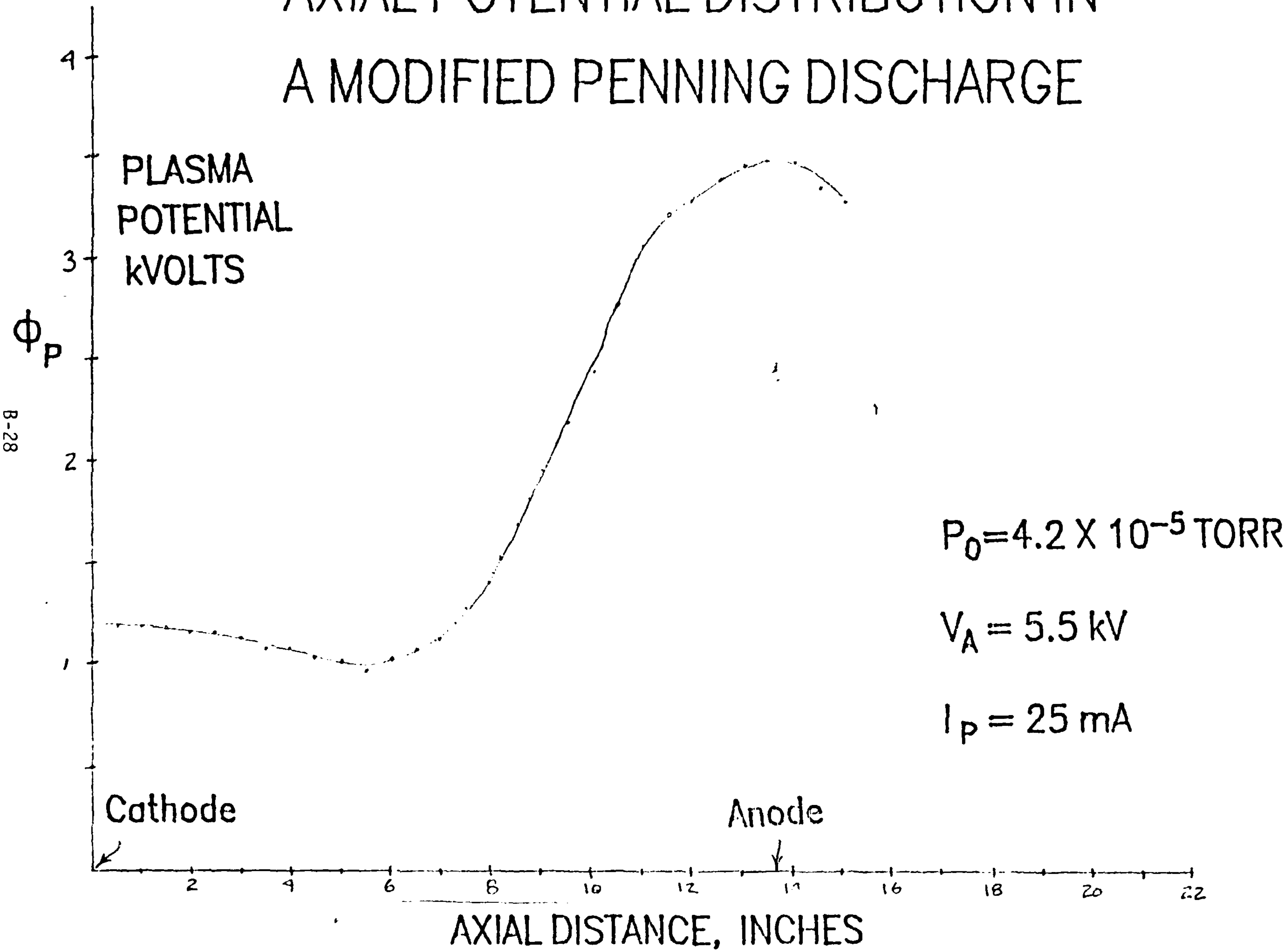
HIGHER MAXIMUM FIELDS ARE POSSIBLE, UP TO .35 TESLA.

THE HIGH MIRROR RATIO, ABOUT 5:1, WAS CHOSEN TO BETTER SIMULATE MAGNETOSPHERIC PLASMAS.

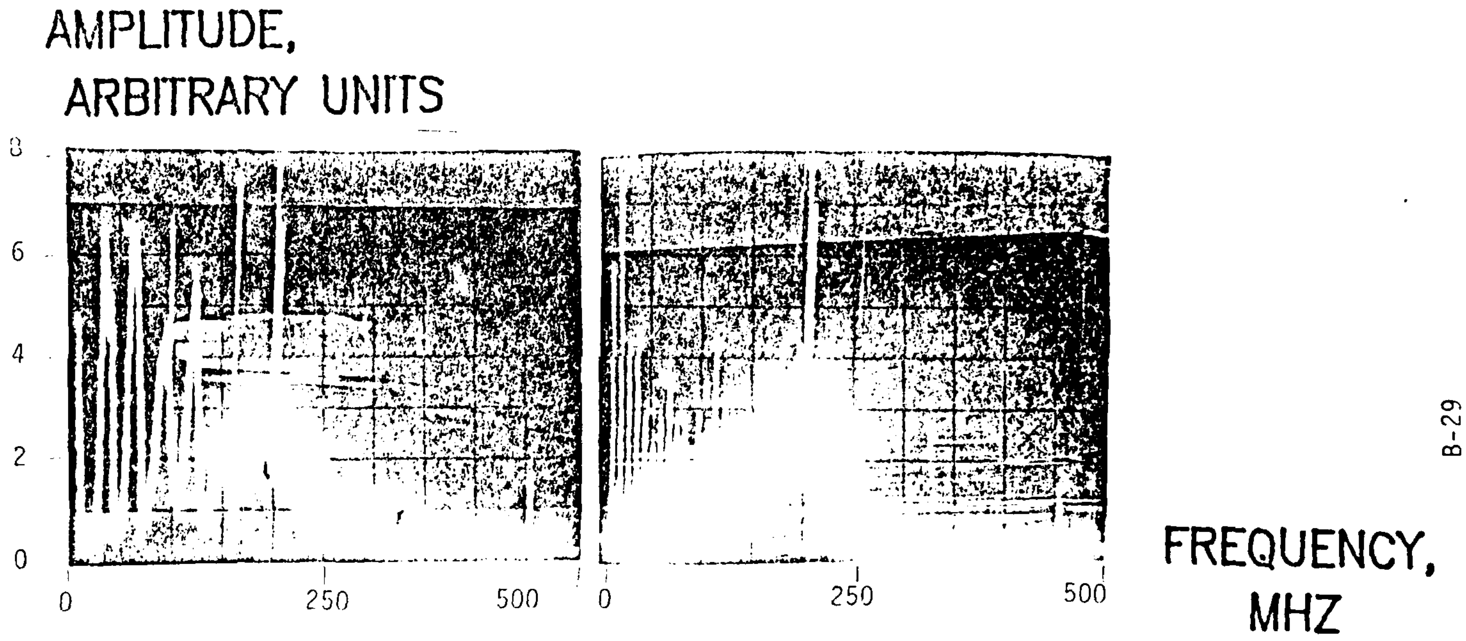


MAGNETIC FIELD, TESLA
.18
.16
.14
.12
.10
.08
.06
.04
.02
5
30
35
40
AXIAL DISTANCE, INCHES

AXIAL POTENTIAL DISTRIBUTION IN A MODIFIED PENNING DISCHARGE



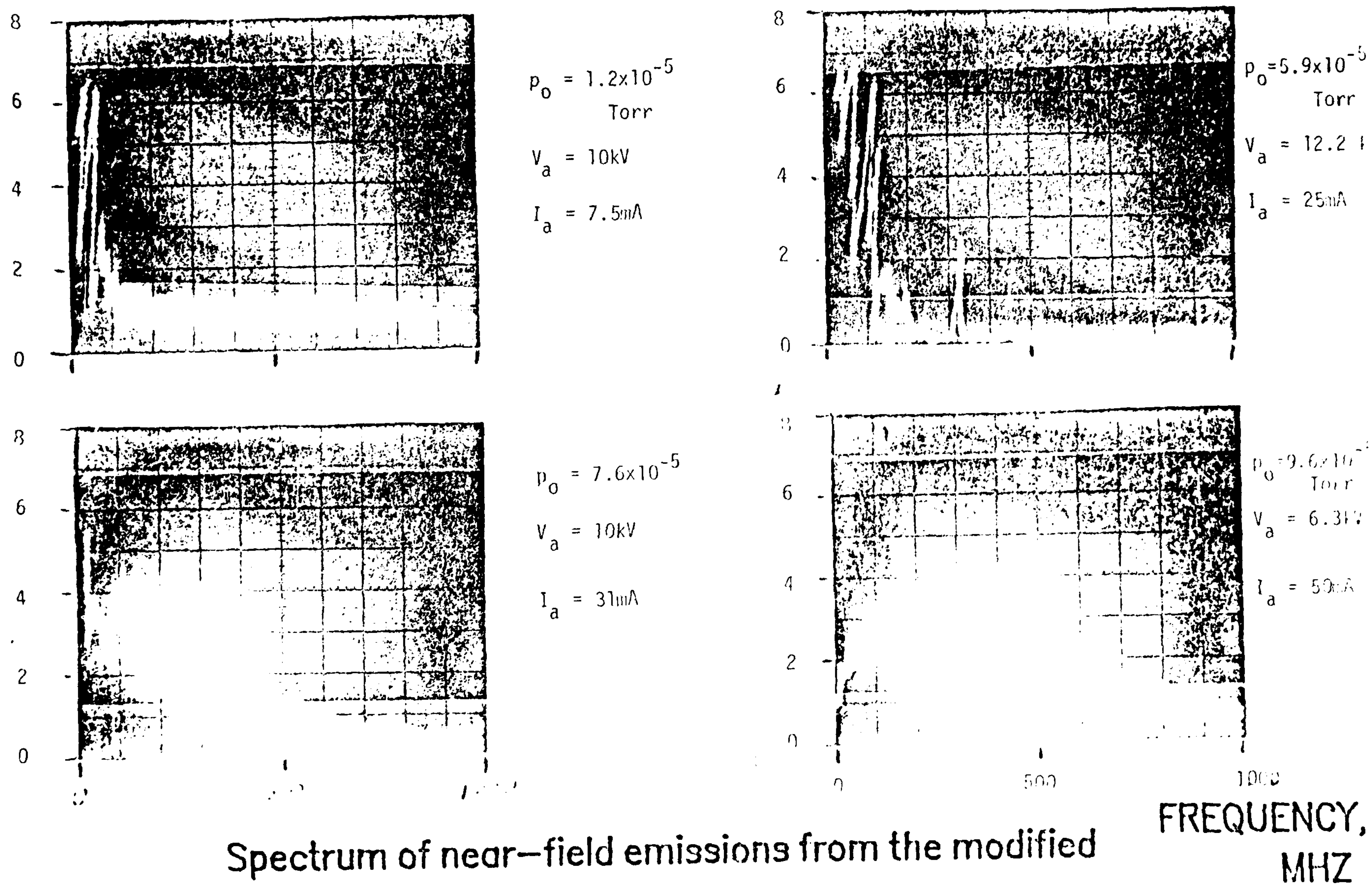
EMISSIONS FROM MODIFIED PENNING DISCHARGE



Spectrum of near-field emissions from the modified Penning discharge operating with helium gas at a 5:1 mirror ratio with B_{max} = 0.38 Tesla.

A) Mode I operation at $p_o = 7.0 \times 10^{-5}$ Torr, electrode voltage V_a = 4.0 kV, and electrode current I_a = 4.0 mA. B) Mode II operation at $p_o = 4.0 \times 10^{-4}$ Torr, $n_e = 9.1 \times 10^9/cm^3$, V_a = 2.0 kV, and I_a = 46 mA.

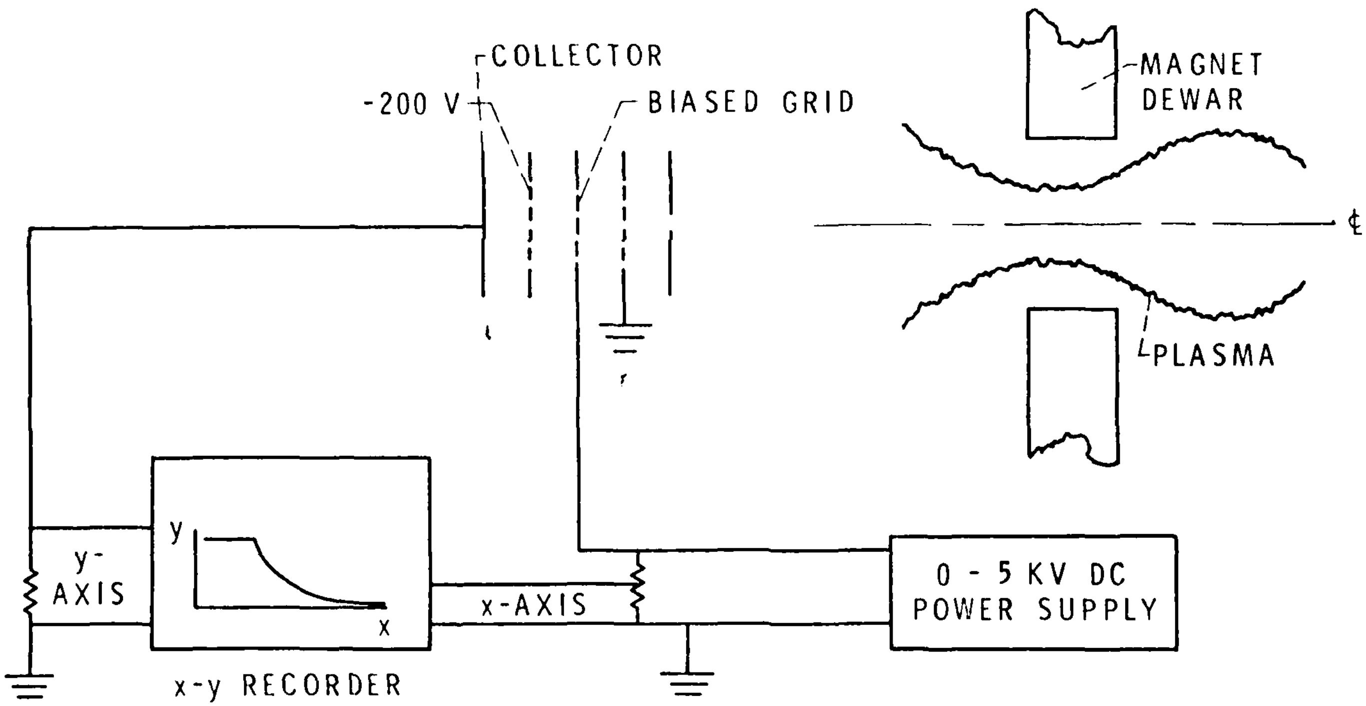
MODIFIED PENNING DISCHARGE



Spectrum of near—field emissions from the modified Penning discharge operating in Argon gas at a 5 : 1 mirror ratio with Bmax = .38 Tesla.

NASA

SCHEMATIC OF ENERGY PROBE



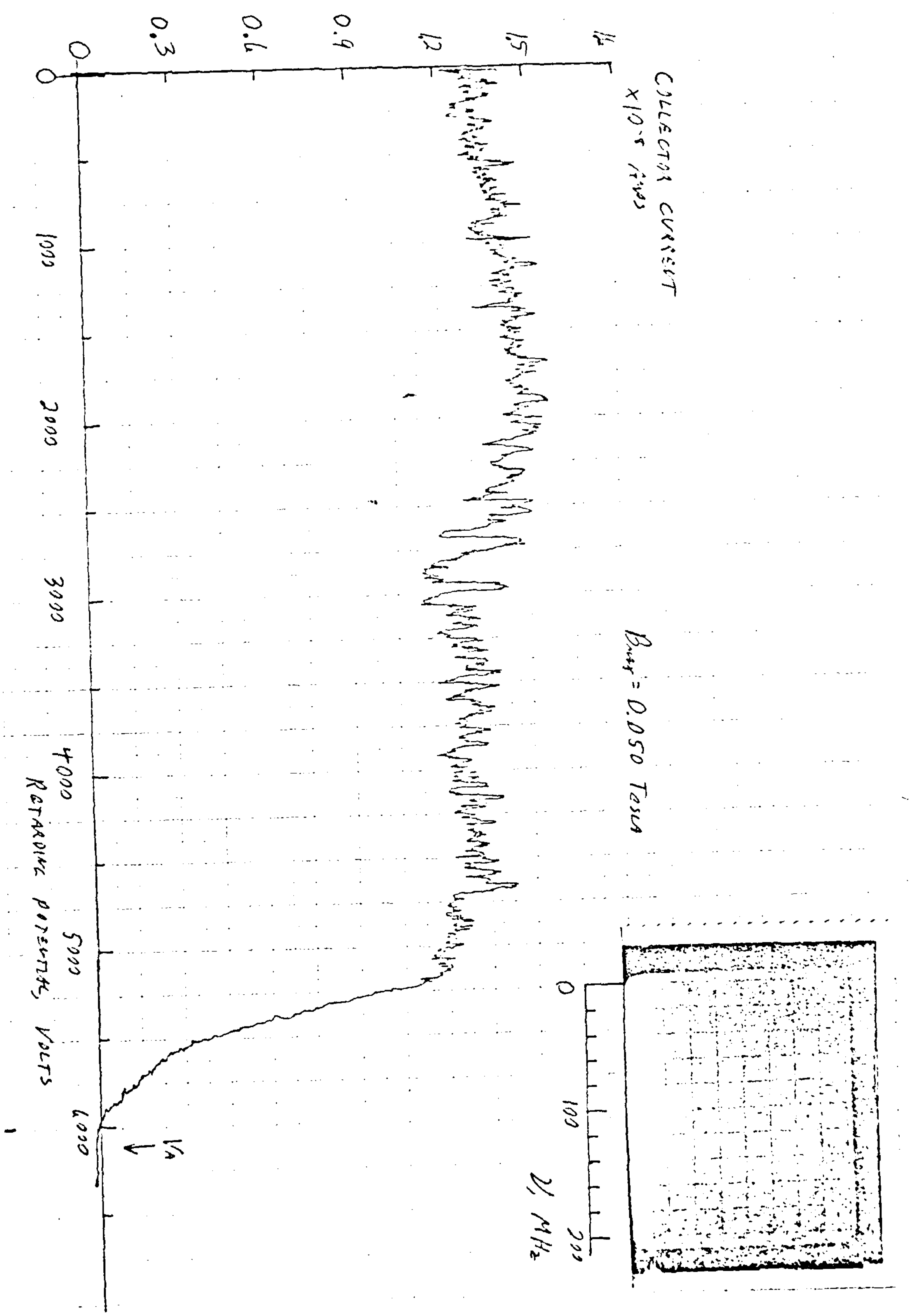
RF EMISSION AND THERMALIZATION OF ION ENERGY PARALLEL TO B AS A FUNCTION OF MAGNETIC FIELD

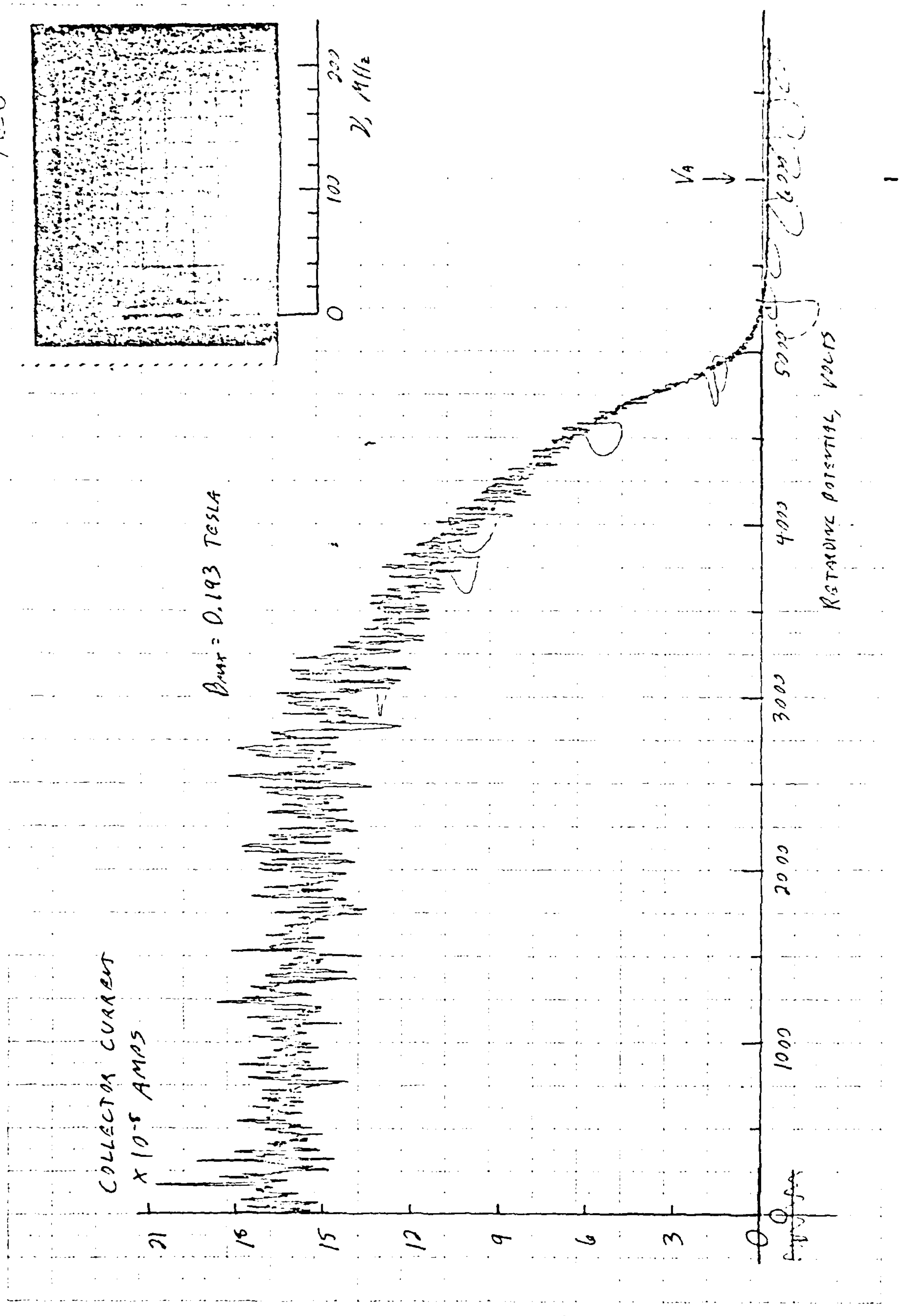
In the data below, RF emission from 0-200 MHz and retarding potential curves were taken simultaneously at several values of the magnetic field, for the following constant conditions:

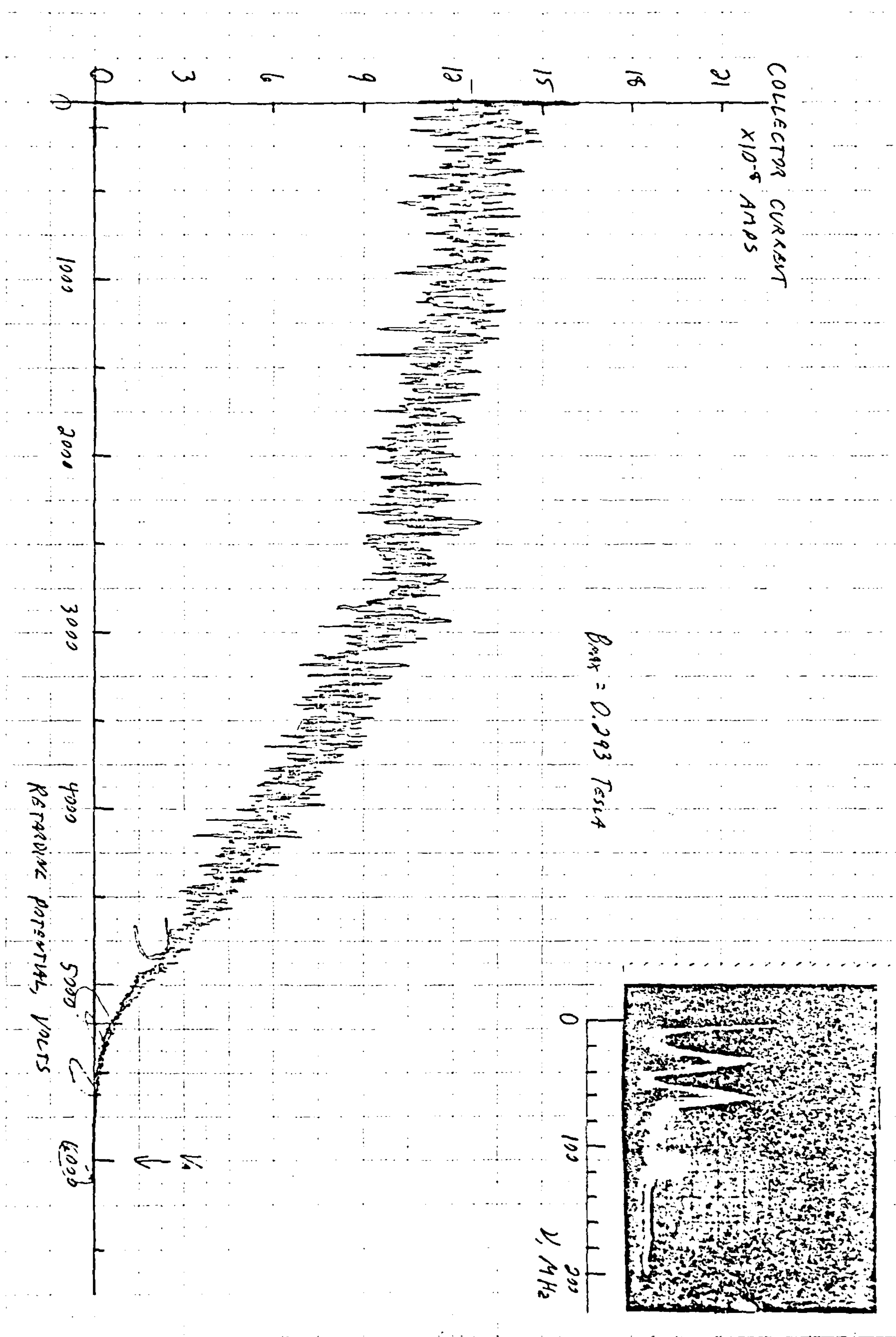
1. Helium Gas

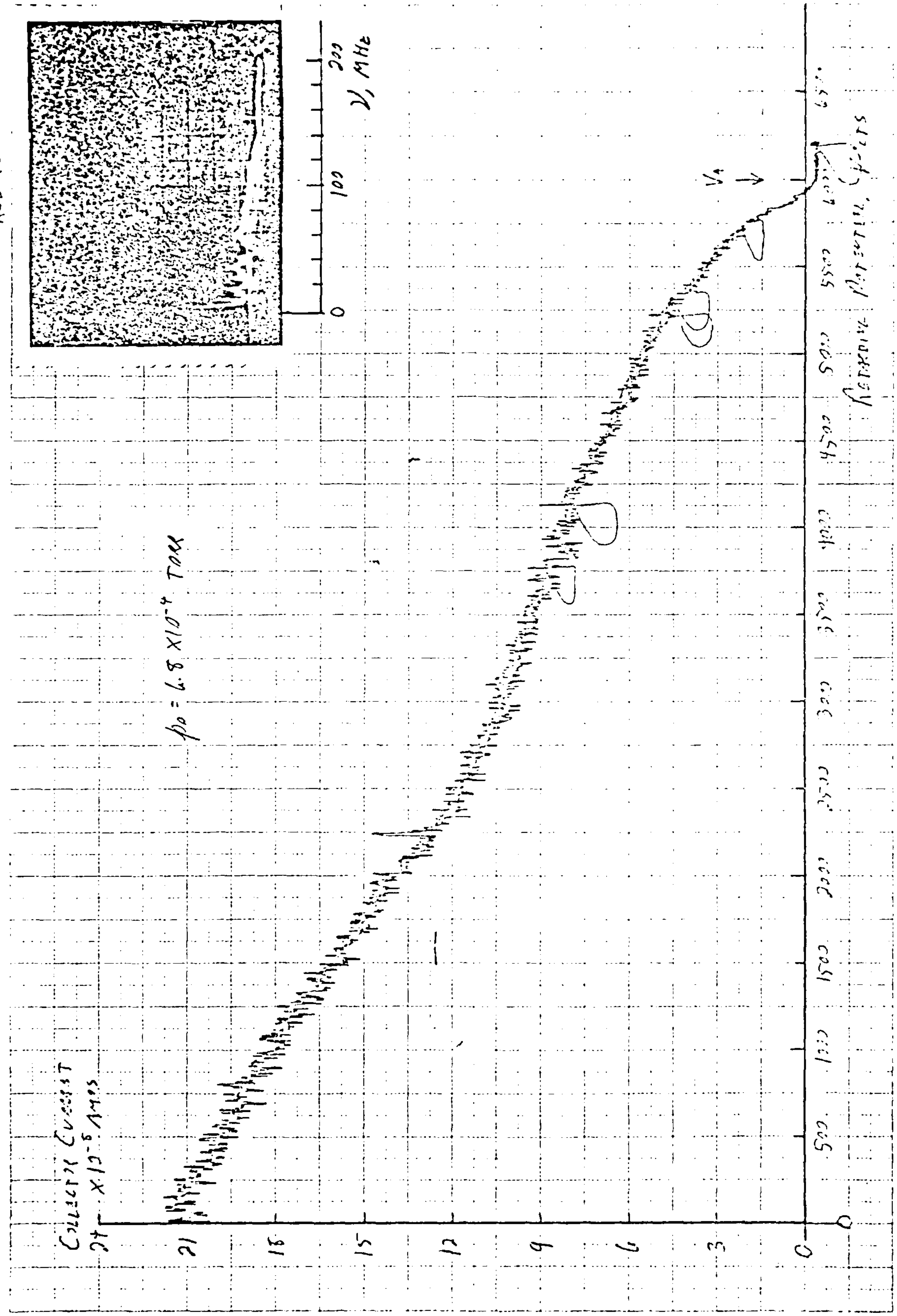
2. Anode Voltage V_A = 6000 volts

3. Helium Density $n_o = 5 \times 10^{12}/cm^3 = 1.4 \times 10^{-4}$ Torr


COLLECTOR CURRENT
0
0.3
0.6
0.9
1.2
1.5
1000
2000
3000
4000
5000
6000
RETARDING POTENTIAL, VOLTS
B_{mag} = 0.050 TESLA
0
100
200
ν, MHz
V_A


AIC-6
COLLECTOR CURRENT
x 10^-8 AMPS
B_max = 0.193 TESLA
RETARDING POTENTIAL, VOLTS
V_A
ν, MHz
0
100
200
21
18
15
12
9
6
3
0
1000
2000
3000
4000
5000
6000

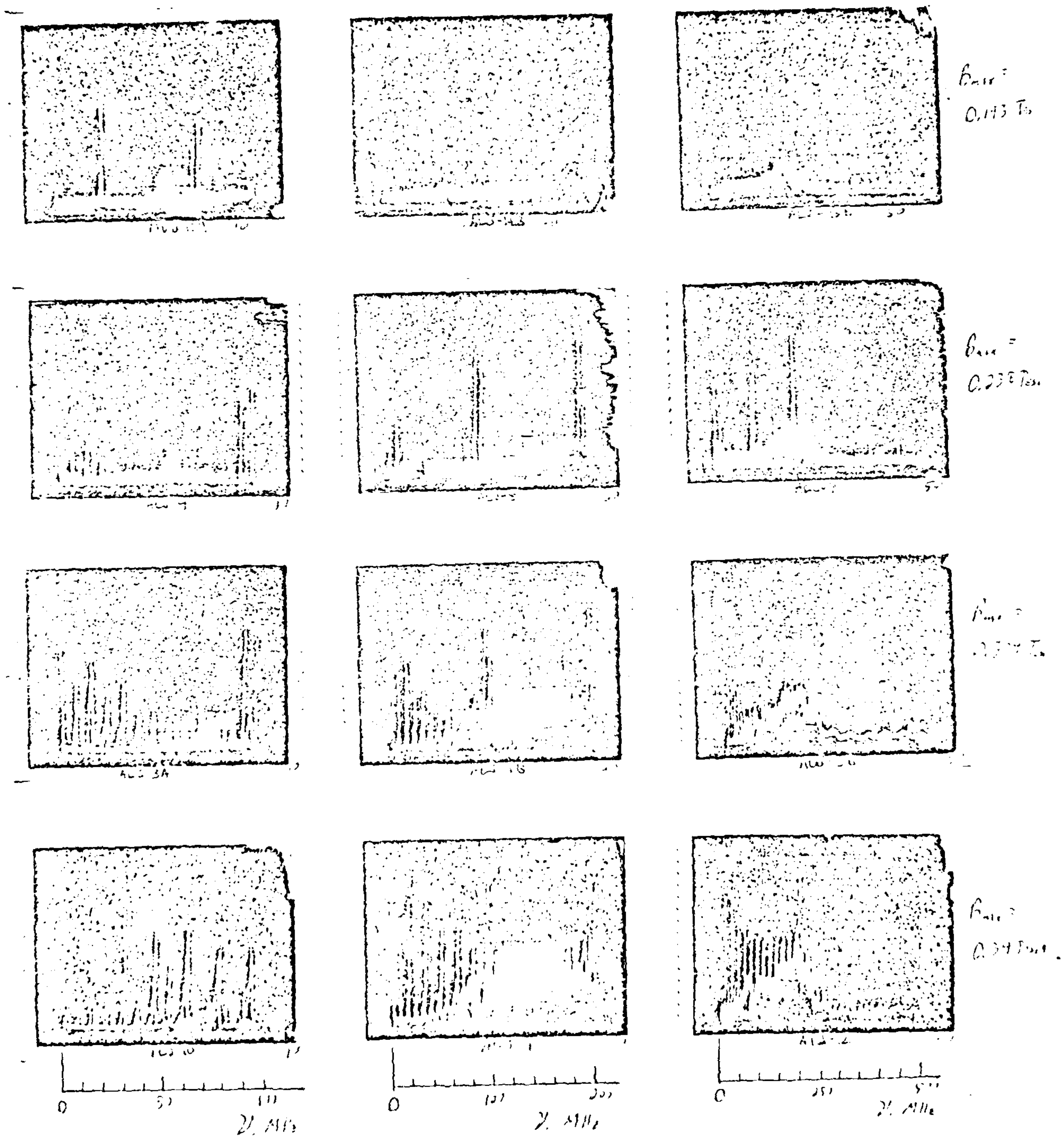

COLLECTOR CURRENT
X10^-8 AMPS
0
3
6
9
12
15
18
21
1000
2000
3000
4000
5000
6000
RETARDING POTENTIAL, VOLTS
V_0
B_{MAX} = 0.293 TESLA
0
100
200
ν, MHz


ACD 12
Collector Current
×10⁻⁵ Amps
p₀ = 6.8 × 10⁻⁷ Torr
ν, MHz
Cathode Potential, Volts
0
100
200
0
3
6
9
12
15
18
21
24
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500

RF HARMONIC GENERATION AS A FUNCTION OF MAGNETIC FIELD

In the data below, RF emission up to 0.5 GHz were taken on a spectrum analyzer with a <u>linear</u> vertical scale as a function of the magnetic field for the following constant conditions:

1. Helium Gas
2. Anode Voltage V_A = 2000 volts
3. Helium Density $n_0 = 1.6 \times 10^{13}$/cm (4.8×10^{-4} Torr)

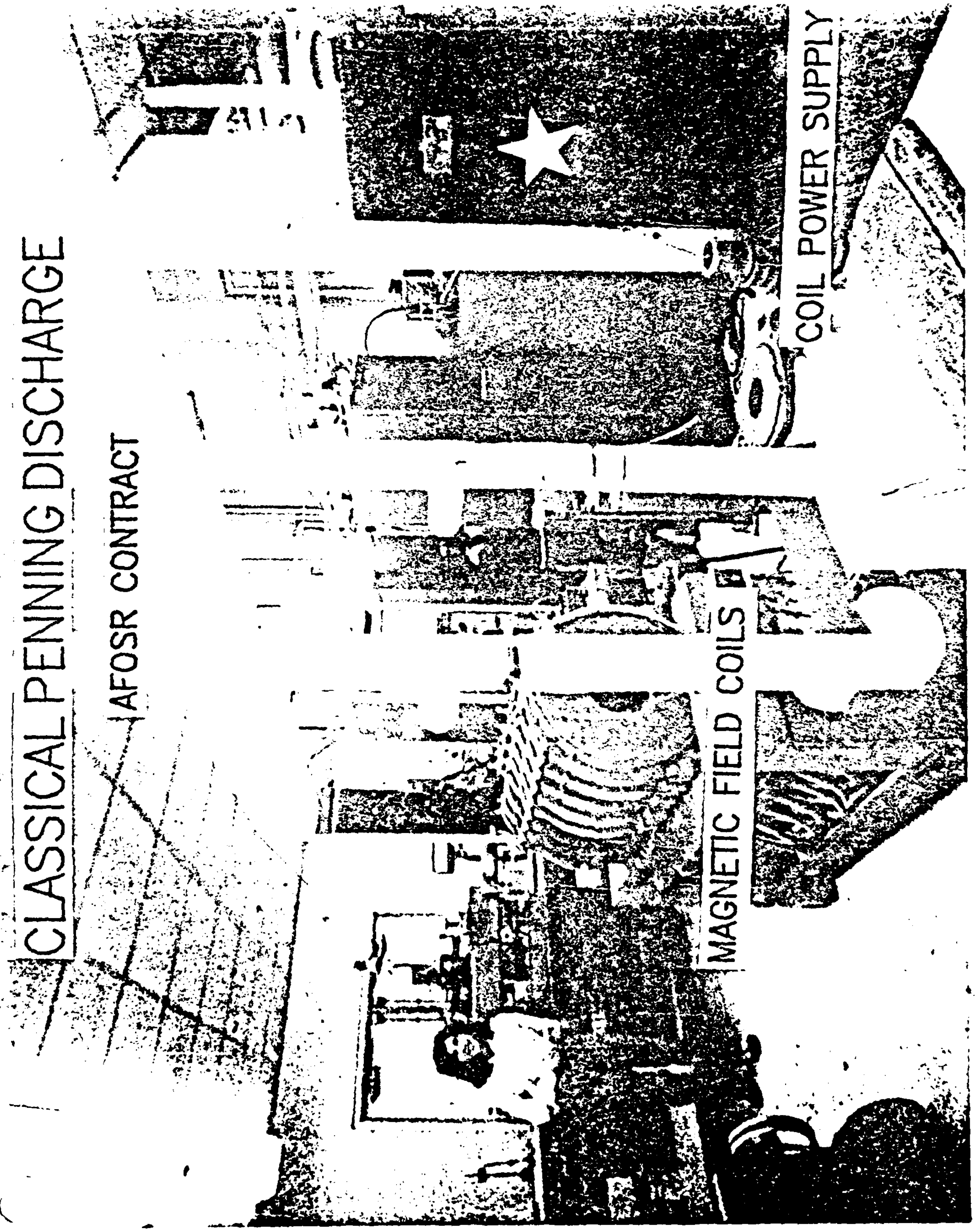


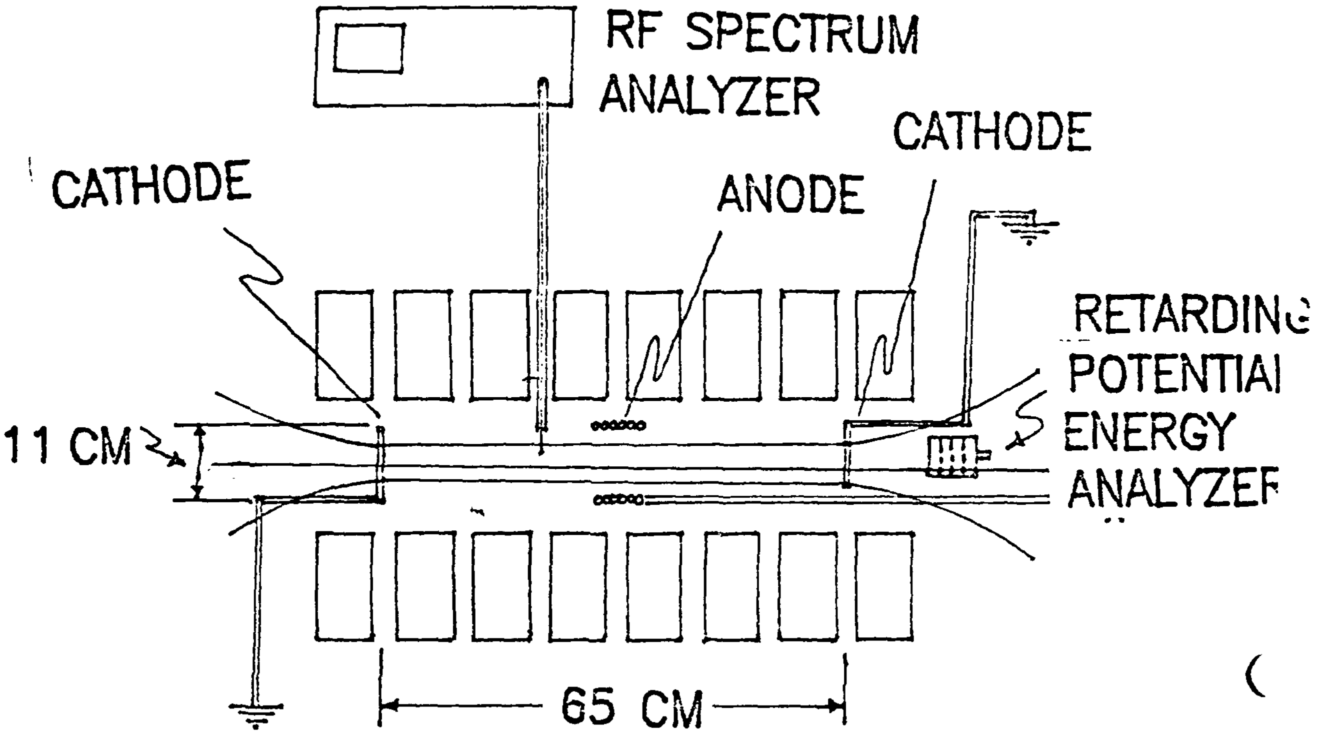
THE CLASSICAL PENNING DISCHARGE

CONSISTS OF A STEADY—STATE PENNING DISCHARGE IN A UNIFORM MAGNETIC FIELD.

EXHIBITS RF EMISSION IN ARGON GAS UP TO APPROXIMATELY 700 MHz.

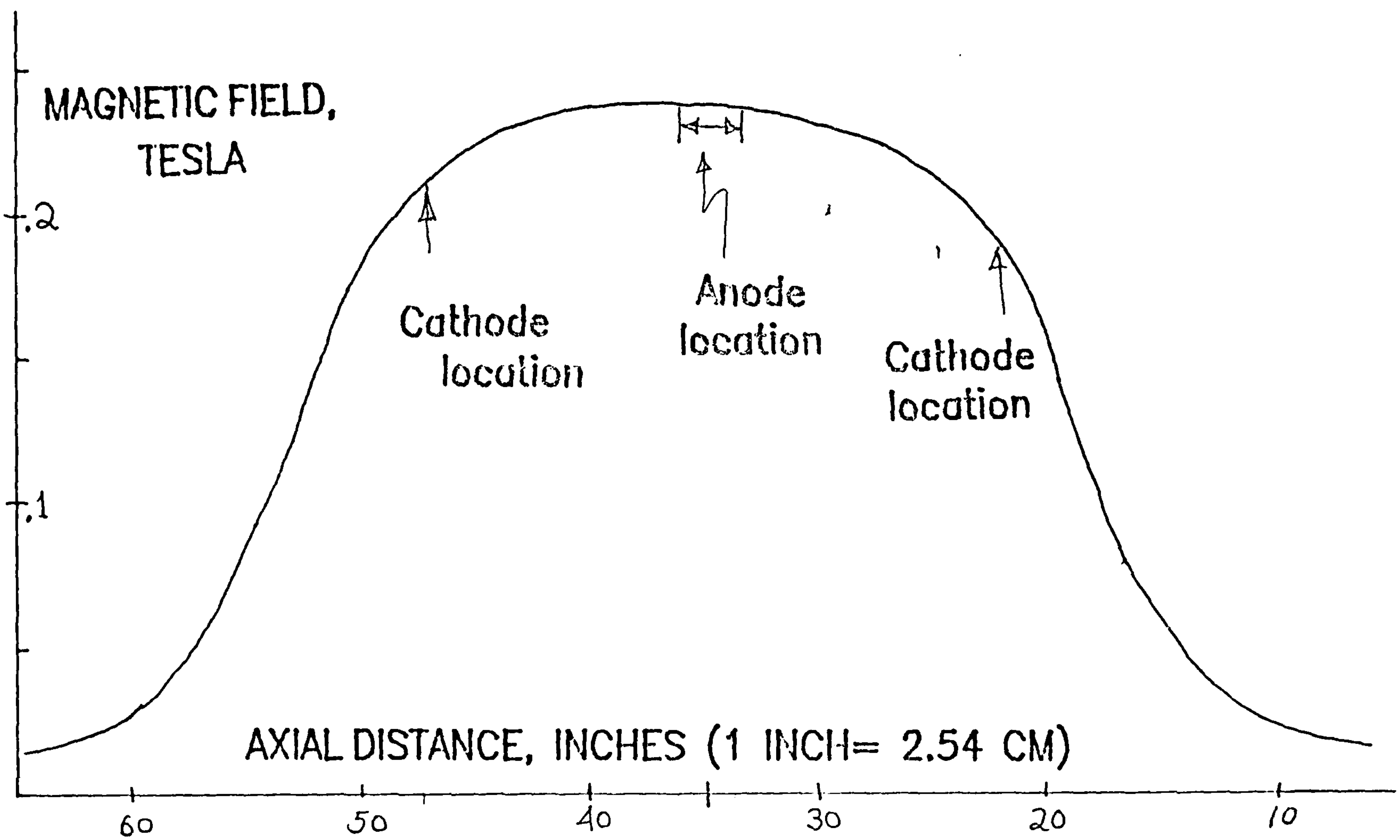
DISPLAYS MUCH NONLINEAR MODE COUPLING AMONG HARMONICS OF THE ELECTRON PLASMA FREQUENCY AND THE GEOMETRIC MEAN EMISSION FREQUENCY.


CLASSICAL PENNING DISCHARGE
AFOSR CONTRACT
MAGNETIC FIELD COILS
COIL POWER SUPPLY

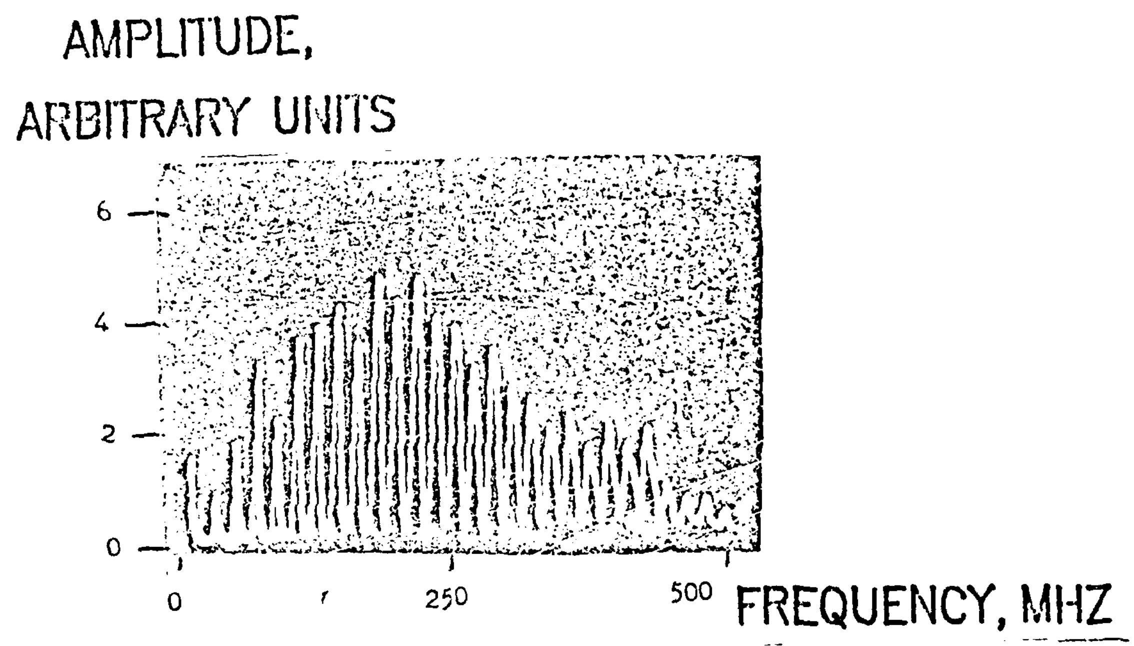


CLASSICAL PENNING DISCHARGE

AXIAL MAGNETIC FIELD PROFILE OF A CLASSICAL PENNING DISCHARGE

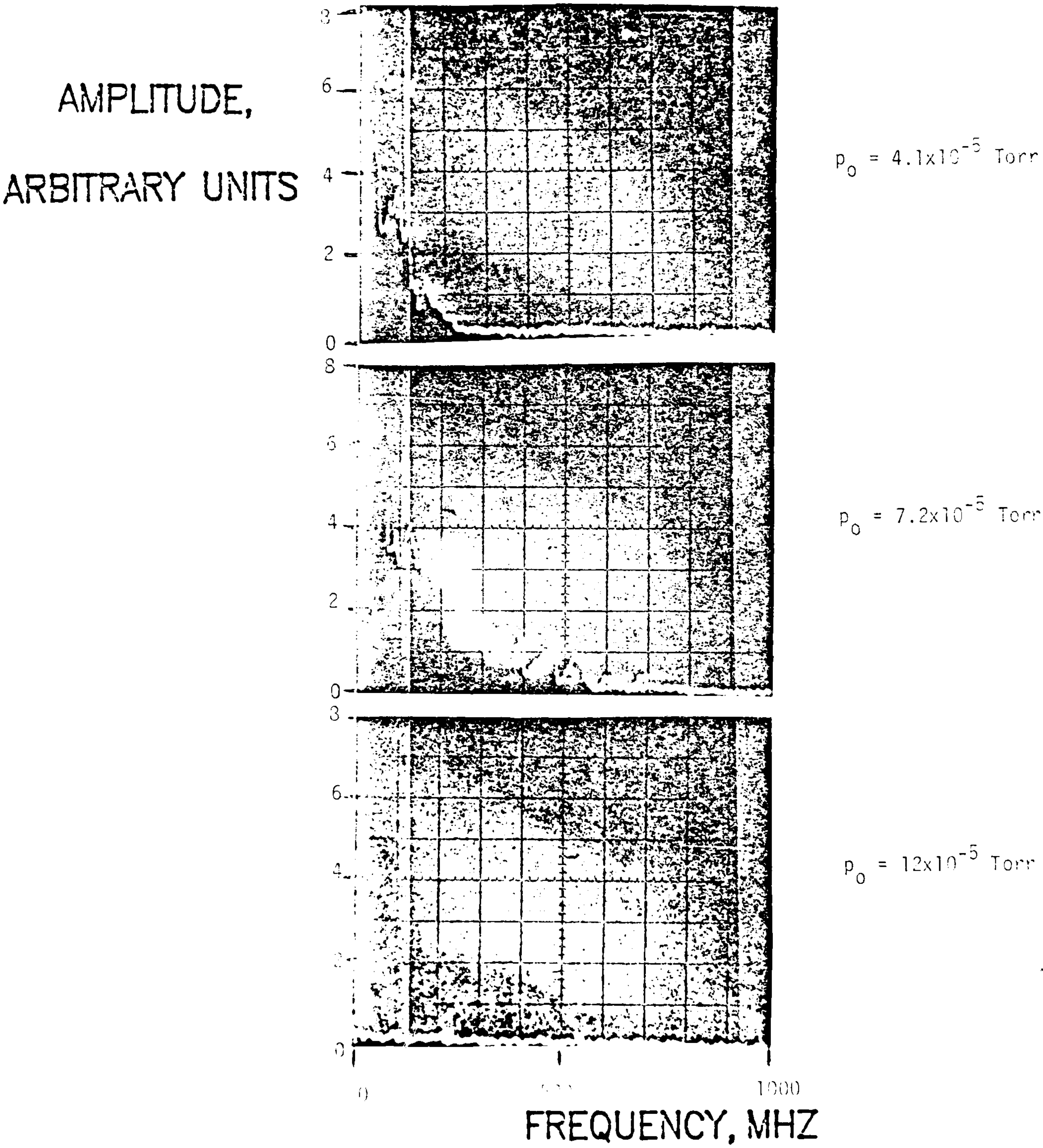


CLASSICAL PENNING DISCHARGE



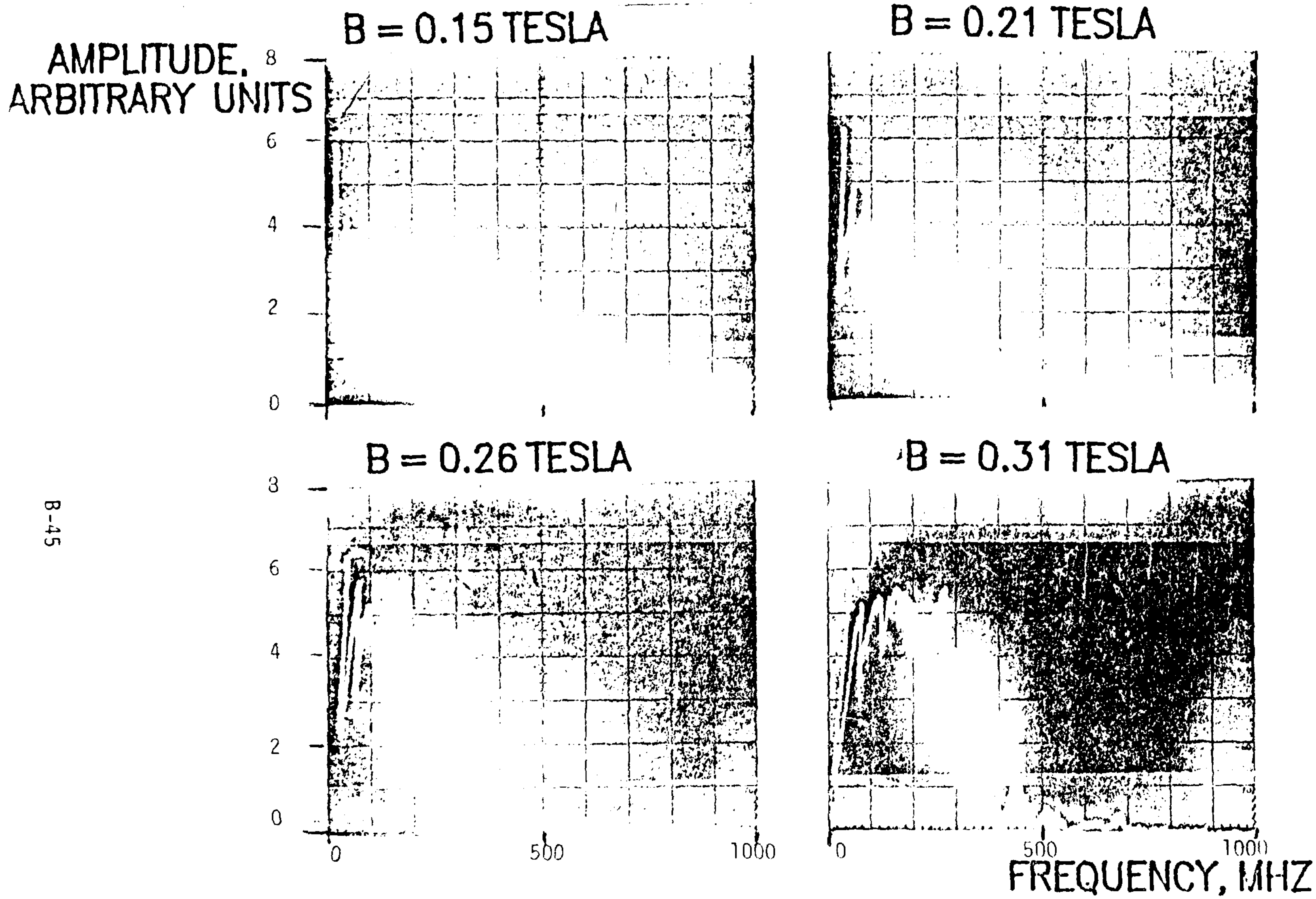
Spectrum of near field emissions from the classical Penning discharge with uniform magnetic field of $B = 0.285$ Tesla, $p_o = 2.3 \times 10^{-4}$ Torr of Argon gas, electrode voltage $V_a = 2.1$ kV, and electrode current $I_a = 31$ mA.

CLASSICAL PENNING DISCHARGE



Spectrum of near–field emissions from the classical Penning discharge operating with Argon gas and a magnetic field B = 0.24 Tesla.

CLASSICAL PENN''G DISCHARGE



Spectrum of near–field emissions in Argon gas for

DC electrode voltage $V_a = 6.5$ kV

background pressure $p_o = 6.5 \times 10^{-5}$ Torr.

CONCLUSIONS

BOTH CONFIGURATIONS OF PENNING DISCHARGE EMIT RF RADIATION FROM BELOW 1 MHz TO AT LEAST 1 GHz.

BOTH CONFIGURATIONS DISPLAY MULTIPLE HARMONIC GENERATION AND STRONG NONLINEAR MODE COUPLING.

THE MODIFIED PENNING DISCHARGE CAN EMIT A "WHITE NOISE" RF SPECTRUM, FLAT FROM 0.5 MHz TO 1 GHz.

STRONG RADIAL ELECTRIC FIELDS (0.1–1.0 KV/CM) EXIST IN BOTH CONFIGURATIONS.

AXIAL ELECTRIC FIELDS OF ABOUT 100 V/CM HAVE BEEN OBSERVED IN THE MODIFIED PENNING DISCHARGE.

LONGITUDINAL ION ENERGIES OF ABOUT 1 KeV HAVE BEEN OBSERVED IN THE MODIFIED PENNING DISCHARGE.

APPENDIX C

TRIP REPORT

M E M O R A N D U M

TO: Dr. Michael A. Stroscio, Program Manager, AFOSR

FROM: Dr. J. Reece Roth, Principal Investigator, Contract AFOSR-81-0093.

DATE: 15 July, 1982

SUBJECT: Trip Report on the 1982 International Conference on Plasma Physics, Goteborg, Sweden, and Related Travel.

The Air Force Office of Scientific Research, Bolling Air Force Base, supported my participation in the 1982 International Conference on Plasma Physics, held in Goteborg, Sweden, June 9-15, 1982, where I reported on AFOSR sponsored research. A quirk in the airlines pricing policy allowed me to stay overseas for 2 weeks about $500 more cheaply than it would have cost to come back after 1 week at the end of the conference. I used the additional week to attend and give a paper at the Symposium on New Trends in Unconventional Approaches to Magnetic Fusion, which was held in Stockholm on June 16-18, 1982, and to stop at the Culham Laboratory near Oxford, England, on Monday, June 21st, where I renewed acquaintance with several of my collegues, gave a seminar, and had an opportunity to visit the site of the JET (Joint European Torus) experiment. My time overseas extended from June 8, to June 22.

The Goteborg conference was the second joint conference of the Kiev International Conference on Plasma Theory, and the International Congress on Waves and Instabilities. This was the fifth occasion on which the latter two conferences met, and the second time which they have met jointly. The conference appears to have been a great success. 36 countries were represented, with an unusually heavy representation of scientists from the USSR and Eastern Europe. There appeared to be unusually few no-shows among the Soviet block scientists. This participation was probably facilitated by the association of this conference with the Kiev conference, and the fact that it was held in a neutral country. There were about 36 countries represented at this meeting, 450 scientific papers were presented in parallel sessions, and at least 500 individual scientists attended the meeting. Once we arrived at the meeting site, the meeting turned out to have been very well organized, with all scientific and informal sessions appearing to go smoothly.

The United States was well represented at this conference, and almost every big name in US plasma physics was there. A rumor floated around the conference that the Nobel Prize Committee in Physics wishes to honor other branches of physics than high energy and solid state, such as plasma physics.

Representatives of this Committee were said to be in the audience, looking over some of the invited speakers who are candidates for a Nobel Prize in the plasma-fusion energy area. Hence, we heard invited talks by Marshall Rosenbluth, Richard Post, Harold Furth, and leading contenders for the Nobel Prize from other countries including the USSR. Most of the universities, national labs, and industrial organizations from the United States were represented at this meeting, but the Oak Ridge National Laboratory was conspic''ous by its absence. Only two individuals from ORNL participated in this meeting, and they presented contributed papers. One of the ORNL representatives remarked that this conference had not been well publicized within ORNL, and that attendance was discouraged by the lab policy of withholding final permission to attend conferences until a few days before they were scheduled to leave. Thus, this individual received approval to attend on the Friday before he was scheduled to leave on a Monday!

For those who wish more detailed information about the conference, I have an outline of the sessions of the conference, a participant list, and a Proceedings volume, which contains papers describing the work presented at the meeting.

The opening session of the conference at 9:00 Wednesday was held with the customary European flair for pomp and ceremony. There were flowers on the stage. The welcoming address was made by the Chairman of the International Organizing Committee of the Conference, Professor Hans Wilhelmsson, who outlined the history of this conference and its evolution from the Kiev Conference and the Congress on Waves and Instabilities in Plasmas. He also emphasized the restriction of this conference to hot plasmas, wherever found, as opposed to gaseous discharge plasmas. We then had a short speech by Professor Kai Siegbahn, President of the International Union of Pure and Applied Physics. He attempted to put this meeting in the context of international physics research. He pointed out that there are approximately 10,000 plasma physicists in the world community, of which about 2,500 are in the USA. We then had a short speech by Dr. Alan Gibson, who is Chairman of the Plasma Physics Division of the European Physical Society. He welcomed everyone on behalf of the EPS, one of the sponsors of this meeting, and made the point that the importance of such a meeting as this was to get everyone out of the narrow molds of our individual fields of effort. Finally, we had a short speech by King Carl Gustaf of Sweden, who formally opened the conference with a short welcoming speech in which he expressed his awareness of the world energy problem and the importance of high temperature plasma physics and fusion energy in its solution.

MAJOR DEVELOPMENTS

The technical sessions of the conference opened with invited plenary papers by two of the grand old men of plasma physics, both of whom took the opportunity to announce/encourage major paradigm shifts in the understanding of plasmas. D. ter Haar of the UK spoke on the physics of hot plasmas. He contrasted the state of plasma theory now as opposed to that at the first Kiev Conference on Plasma Theory in 1971. One of the major trends which he identified was the growing interest in, and understanding of, plasma turbulence. In his discussion, he distinguished between fast and slow oscillations, associated respectively with electron and ion characteristic frequencies. He discussed the cascading of energy in frequency space, up or down the turbulence spectrum. He posed a question to the audience, that is yet to be determined, as to what extent ordinary fluid turbulence is a guide to the understanding of plasma turbulence. He suggested that the proper small parameter for plasma turbulence theory was the quantity which can be though of as the ratio of the electrostatic pressure to the plasma pressure,

$$\varepsilon^2 = \frac{\varepsilon_0 E^2}{2nkT} << 1$$

The inverse of this quantity would be the electrostatic analog of the plasma instability index beta, familiar from magnetic confinement theory. Ter Harr's emphasis on the importance of plasma turbulence to understanding the behavior of hot plasmas was good to hear, and exactly coincided with my own views on the subject. Many of the possible future directions of research which he mentioned in his talk are ones which are part of the program here at the UTK Plasma Science Laboratory.

The second invited talk was by Hannes Alfven, the only living Nobel Prize winner in plasma physics, who spoke on "Paradigm Transition in Cosmical Plasma Physics". In this talk, Alfven discussed the changes in our basis of understanding cosmical plasmas (and by extension, of hot plasmas in general) from the older macroscopic fluid description, to the more nearly correct kinetic or individual particle description. The latter has come into increasing use since 1960, and has made possible a correct understanding of many phenomena which are only qualitatively or incorrectly understood by the older fluid theory. An interesting aspect of Alfven's position is that his textbook Cosmical Electrodynamics was the seminal reference for the older fluid theory. Since winning his Nobel Prize about 10 years ago, Alfven has attempted to hasten this paradigm shift. He pointed out that the kinetic approach has resulted in a complete change in the basis for understanding magnetospheric plasmas. He remarked that the fluid theory first collapsed in the field of fusion energy, then in the theory of the magnetosphere, and is now in serious trouble as a theoretical approach to understanding large-scale astrophysical phenomena such as interstellar clouds. He pointed out that electric double layers in the magnetosphere, which have been observed by satellites and which were a major topic at this conference, could not be properly understood by a fluid theory, but were correctly described by the kinetic or single particle approach. Another matter that was of concern to Alfven was an aspect of the old fluid MHD theory in which magnetic field lines were regarded as being frozen into conducting fluids. He took full blame for having introduced that concept into astrophysical theory, and pointed out that it should now be laid to rest,

There were two major "buzz-words" or hot topics at this meeting. These were "electric double layers", and "magnetic field line reconnection". A double layer is a structure which can arise in a flowing, magnetized plasma as a solution to the kinetic equations, and which will permit a parallel electric field to develop along an externally imposed magnetic field. The electric field is a reuslt of the Poisson equation, and is sustained by two regions (or a double layer) of charge, one positive and one negative, which maintain the parallel electric field between them. These structures have been observed in the magnetosphere, and more recently in laboratory plasmas. The concept of the double layer has been around for at least 20 years, but it was only very recently, and even at this conference, that their existence could be said to have been widely accepted. There were a remarkably large number of theoretical and experimental papers on electric double layers, which was probably reinforced by a three-day workshop on the subject held in Sweden at the close of this conference.

The concept of magnetic field line reconnection got quite a bit of play, both in an astrophysical context (solar flares) and in the context of fusion energy (spheromak production, compact tori formation). Magnetic field line reconnection looks like the last gasp of the old fluid MHD theories, and occurs when two regions containing hot plasma and with oppositely directed magnetic fields contact each other. When this happens, the magnetic energy stored in the magnetic fields is fed into the plasma and heats it to produce a solar flare or other similar phenomena. Magnetic field line reconnection occurs in Marshall-type plasma guns, railgun accelerators with plasma armatures, spheromak production, etc. When these structures are formed, the forces acting on the plasma usually stretch out the magnetic field lines embedded in the plasma as well as the plasma itself, until the plasma, in being hurled away from the fixed source, reaches the "breaking point". The magnetic field lines are pictured as reconnecting to each other within the plasma and disconnecting from the source.

An interesting major development in the field of fusion energy was a new physical process for achieving a steady-state current drive for toroidal devices, like the tokamak, that required a toroidal current for stability. One of the most serious drawbacks of the tokamak concept for powerplant fusion reactors is the fact that it in principle is a cyclic device, in view of the natural tendency of the ohmic heating current in the toroidal direction to dissipate through Ohmic heating of the plasma. A very clever mechanism to sustain this toroidal current in toroidal plasmas was put forward by John Dawson of UCLA. He suggested that the electron drift velocity in the toroidal direction could be maintained by synchrotron radiation pressure. When the electrons in a fusion plasma exceed about 30 keV, enough synchrotron radiation is produced by the plasma to have a significant effect on the energy and momentum balance of the plasma. It was suggested by Dawson that the plasma be surrounded, around the minor circumference, by annular mirrors and absorbers, arranged in a "fish scale" pattern, such that all of the synchrotron radiation circulating around one sense of rotation in the toroidal direction is absorbed, and all radiation circulating in the opposite sense is reflected. This preferential absorbtion of synchrotron radiation would then preferentially impart momentum to the electron population producing this radiation, and drive currents around the torus. Dawson presented calculations which indicate that for 30 to 50 keV electron temperatures, fusion plasmas may produce enough radiation reaction force on the electrons to sustain ohmic heating currents of a magnitude required for fusion reactors.

A final major development which emerged at this conference was a proposal made by a Harold Furth et al. of Princeton to control fusion reaction rates by controlling the degree of polarization of the fusionable fuel nuclei. It seems that by proper fueling techniques, it is possible to polarize the light element nuclei that are to undergo fusion reactions, with respect to the confining magnetic field. Once the nuclei are polarized, this places constraints on the types of reaction which those nuclei will undergo. By properly arranging the polarization between the nuclei of deuterium and tritium, for example, it should be possible to enhance the reactivity of the DT reaction by a factor of 1.5 above the published values. An even more intriguing possibility may exist in the case of the DD reaction. Here, if the polarization of the two nuclei have the proper relation to each other, it is possible to almost completely supress the neutron-producing branch of the DD reaction, while enhancing the tritium branch. This therefore may be a mechanism to burn deuterium, while supressing neutrons produced by the primary reaction.

The biggest uncertainty with this concept is whether or not the nuclei will remain in a fixed state of polarization throughout the scattering collisions and other randomizing processes which the fuel of a fusion reactor would normally experience. Harold Furth and his co-authors on this paper have done calculations which seem to indicate that the forces which would depolarize the nuclei in a fusion plasma are sufficiently weak that the depolarization time is longer than the particle confinement time required for a Lawson reactor. If this holds up, it could be a major development in fusion energy, since it would allow one to burn naturally available deuterium without producing intense neutron fluxes and without the necessity of breeding tritium.

OTHER INTERESTING DEVELOPMENTS

Peter J. Barrett from the University of Natal, South Africa gave an experimental paper on turbulent heating in a cross-field ion beam experiment, which ties in well with some work we have done at the UTK Plasma Science Laboratory, and reported at the same meeting. In his experiment, a 27 centimeter diameter beam of argon ions with energies of about 40 eV were generated. The ion beam was neutralized, and then traveled perpendicular to a relatively weak magnetic field, less than 80 gauss. The magnetic field did not significantly affect the trajectory of the ions, but the electrons were tied to the field lines. The argon ions were approximately monenergetic, and the plasma noise levels were quite low. Barrett had a retarding potential energy analyzer which measured the energy distribution function of the ions. This was nearly monoenergetic at low levels of plasma turbulence. As the noise level in the plasma increased, however, the spread of ion energies greatly increased. This result was not too surprising by itself, but Barrett was able to show that the rate at which the ions were heated increased like the 4th root of the noise level for low levels of noise, and was directly proportional to the noise level at high noise levels. In our experiments at UTK, we do not start with a clean-cut monoenergetic ion distribution function as did Barrett, but we also have observed spreading of the ion distribution function, and increasing levels of thermalization with increasing levels of rf emission and plasma noise. Barrett, in his experiments, had not made any attempt to observe rf emissions at the same time he was making these energy spreading measurements.

Harold Furth of Princeton gave an invited talk describing some recent results at Princeton, mostly on the PLT. He reported that the increase in ion kinetic temperature in the PLT plasma was a direct function of the neutral beam input power per confined particle, and that this curve was a straight line which did not saturate even at the highest densities and power inputs which they had achieved thus far. This was a very encouraging result, particularly in view of early fears that large amounts of neutral beam heating power might destabilize the plasma as a result of trapped particle instabilities. At Princeton they produced a plot of temperature increase versus power input per particle for both ion cyclotron resonance heating and neutral beam injection. At the same power input per confined particle, ion cyclotron resonance heating was more efficient than neutral beam injection, and led to a larger increase in the kinetic temperature.

In both the PLT and PDX experiments at Princeton, they have achieved values of the plasma stability index, beta, up to about 3%, and then have difficulty with instabilities above that level. This is a rather low value for power reactors, for which they would like to have somewhere between 5 and 10%. In the PDX experiments, when they plot beta versus the input power, the relationship is linear and there is no saturation, which would indicate instability.

During his paper Harold Furth made the interesting admission that they do not understand particle and energy transport in tokamaks. This had been obvious for ten years, but it is only recently that they have felt able to say this publicly, since funding for construction of their large tokamaks is already committed! In addition to their major tokamaks, they are building the spheromak, a device for producing independent blobs of plasma which will resemble ball lightning, but with energy densities of fusion interest. They are also studying a magnetic containment configuration called HELIAC, which consists of helical stellarator windings, with a current carrying conductor on the magnetic axis. This configuration should be stable to betas of at least 25%. The drift surfaces of this configuration have cross sections which look like crescents or bananas, which twist helicaly like thick vines around the center conductor of the configuration.

Richard Post of Livermore gave an invited talk on the physics of mirror systems, in which he reviewed the early history of magnetic mirrors, and then went on to discuss current work at Livermore on tandem mirrors. He pointed out that electrostatic containment was essential in mirrors in order to have adequate containment time for net fusion power production. The ambipolar potentials which result in ion trapping he suggested were controlled by the Boltzmann (barometric) equation, and also by "pumping", the preferential addition or removal of charges by means of ECRH heating or the injection of neutral beams. In the discussion after his paper Post agreed that the Boltzmann equation is a poor theoretical basis for describing the electrostatic potential well in tandem mirror plasmas, since it assumes a statistical-mechanical equilibrium plasma, and all mirror plasmas are very far from kinetic or statistical-mechanical equilibrium. He mentioned that Cohen at Livermore is trying to account for the effect on ambipolar potentials of species-specific escape cone angles.

R. J. Bickerton described the JET (Joint European Torus) scientific program. I will describe more of this in connection with my site visit to JET, but Bickerton pointed out that the dominant aim of JET was to achieve as rapidly as possible a plasma with conditions and dimensions approaching that of a fusion reactor. Indeed, JET is much larger than the TFTR, and very nearly as the INTOR and/or FED reactors. Table I gives a set of parameters for JET and the INTOR reactor, taken from a slide presented by Bickerton. They are hoping to get their first plasma in JET sometime in June or July of 1983, and they intend to operate for their first year with ohmic heating only. They have designed JET to operate after 1985 with 10 megawatts of neutral beam injection, and 15 megawatts of ion cyclotron resonance heating. The neutral beam injection power will be applied first, and then the ion cyclotron resonance heating will be installed on and after 1985. Bickerton stated explicitly that it was not their aim to understand tokamak physics. In the discussion period he admitted that European electric utilities are not at all aware of the situation in fusion research. An interesting aspect of the JET design is that it does not have a divertor of any kind.

This paper was followed by a paper by Engelmann from the Netherlands on the physics requirements for a tokamak engineering test reactor. The tokamak engineering test reactor is the European equivalent ofthe fusion engineering device (FED) in the United States. This is intended to be something beyond the INTOR generation of reactor and would be, if it ever comes to fruition, a European project.

There was an interesting paper on fractal analysis of power spectra by S. Johnson of the USA, in which he applied topological theorems to plasma turbulence in a way that seemed totally devoid of physical insight or information about physical processes. There also was a paper on computer

TABLE I

DEVICE	MAJOR RADIUS R	MINOR RADIUS a	VERTICAL ELONGATION $k = h/a$	ASPECT RATIO R/a	MAGNETIC FIELD, B_o TESLA	OHMIC HEATING CURRENT I,MA
JET	3	1.25	1.6	2.4	3.5	5.0
INTOR	5.2	1.20	1.6	4.4	5.5	6.4

DEVICE	SAFETY FACTOR q	FLAT-TOP DURATION T	AVERAGE DENSITY n, M^3	ION TEMPERATURE T_i, keV	$\beta(\%)$	β_p	τ_E, SECONDS
JET	2.9	13 SEC	$9x10^{19}$	7	4.4	1.4	1.0
INTOR	1.9	∞	$1.4x10^{20}$	10	3.9	1.6	1.4

simulation of plasma turbulence in open systems by Yu. S. Sigov of the USSR, who attributed many aphysical results in this field to the imposition of periodic boundary conditions and the requirement of fixed total energy in the system, since most real systems have large energy inputs that maintain the high levels of turbulence of interest.

Russel M. Kulsrud of Princeton gave an invited talk on plasmas in astrophysics in which he discussed magnetic reconnection and collisionless interactions, all the time using the older and by now discredited MHD and frozen-in field line models. He proceeded to discuss these two phenomena in the context of a wide variety of astrophysical observations, most of it, in my judgement, being simply hand-waving which made no quantitative predictions, and much of which would not stand up if analyzed on the basis of kinetic theory arguments. In discussion, he was asked about the validity of this older MHD model, and admitted that his approach was valid only for very large-scale phenomena, at and beyond the scale size of interstellar distances. Ravi Sudan of Cornell gave an interesting talk on the spectra of magnetic field fluctuations in a turbulent fluid, in which he attempted to tie plasma turbulence to the large body of information on classic fluid dynamic turbulence. He used mixing length theory to establish a time scale based on the eddy turn-over time, the fluid velocity, and a characteristic scale size of the phenomena.

Bruno Coppi of MIT gave a paper on the near-term feasibility of advanced fuel fusion reactors, in which he recognized my recent contributions in this area. He made the point that it would be very desirable to demonstrate the near-term feasibility of advanced fuel fusion reactors and pointed out some of the economic, social, and engineering difficulties associated with developing the DT fusion fuel cycle, particularly in the low-beta tokamak configuration. He proposed to develop high-beta tokamak experiments in which deuterium and tritium would be used for start-up by ohmic heating alone, and then the plasma would be allowed to run away thermally to high kinetic temperatures which would allow them to bleed in helium-3 and fuel the reactor with deuterium and helium-3. He discussed a small size, high beta D^3He tokamak based on the Alcator-C called CANDOR, which would generate a total fusion power output of 100 megawatts, of which 53 megawatts would be thermal power, 33 bremsstrahlung, 10 megawatts in synchrotron radiation, and 4 megawatts of neutron production.

I next attended a session of contributed papers, most of which dealt with turbulence and astrophysical plasmas. Many of these papers were attempts to analyze satellite data, which were interpreted as various maifestations of plasma turbulence. It would seem that the field of magnetospheric or astrophysical plasma turbulence is significantly behind the state of understanding and data base that has been developed in recent years in fusion research and/or high temperature laboratory plasma research, as inadequate as the latter is.

E. Mazzucato from Princeton gave an interesting paper on recent observations on microturbulence in the PLT tokamak. They looked at the spectrum of small scale density fluctuations in the PLT in an attempt to understand the radial transport processes. They concluded that transport in the PLT tokamak remains completely mysterious. The ions appear to behave classically insofar as their transport of energy is concerned, but the electrons do not. They apparently have no idea what physical process is responsible for anomalous transport in the PLT tokamak. They have found that drift wave transport processes do not scale properly to explain the observations. Significantly, they have observed plasma rotation, with a frequency between 1 and 2 kilohertz. He remarked that this could be due to a radial electric field if the plasma in the PLT had a negative floating potential. This drift velocity reverses when they reverse the direction of the toroidal magnetic field. They find a total voltage drop across the radius of about 1500 volts over a radial distance of about 30 centimeters. This gives rise to a radial electric field on the order of 50 volts per centimeter in the ohmically heated tokamak. When they attempt to look at the electric potential fluctuations with energetic neutral injection, they find that when they apply more than about 3 megawatts of neutral beam injection power, there is so much turbulence their instrumentation is saturated and cannot measure it. Under these conditions, they do not know the electron energy containment time in the plasma and they do not accurately know the amount of power deposited in the plasma.

In a post-deadline paper, H. Berk of the University of Texas at Austin gave a paper on the MHD stability of EBT plasma. This paper was extremely disappointing. The basic approach was the old fluid MHD analysis, and completely left out of consideration radial eelctric fields. Electric fields ranging from 10 to 50 volts per centimeter are known to exist in the EBT plasma, so there is really no excuse for pursuing a theory which neglects them, and Berk admitted as much in the question period after his paper.

Marshall Rosenbluth gave a major invited paper on plasma instabilities, in which he spent about the first half-hour reviewing the current status of instability research for fusion applications. Interestingly, he defined micro-instabilities to be those instabilities which have an electric field parallel to the magnetic field. He spent the second half of his review lecture describing some recent work on the stability of tandem mirrors,which indicates that tandem mirrors may have a low frequency MHD instability as a result of the region of unfavorable curvature in the central portion of the mirror.

Forrest Jobes of Princeton gave a talk on current drive on the PLT experiment. They operate with lower hybrid heating and feed the RF into the plasma with a waveguide array. They showed a photograph of the waveguide array in operation at a level of several megawatts, and at that point there was no sparking visible-a common problem in RF heating of this type. They were able to sustain current with a zero loop voltage for a period of 1 second, and the coupling was best at number densities between 2 and 4 x 10^{12} particles per cubic centimeter. The efficiency of the current drive dropped drastically above densities of about 6 x 10^{12} particles per cubic centimeter. A high density limit may exist for RF current drive, and may be a serious limitation of this method. In addition to sustaining the ohmic heating current for 1 second with no loop voltage around the torus, they actually increased the ohmic heating current and the electron number density with the RF current drive.

Tsytovich from Russia gave a paper entitled "A New Mode Coupling Process in Plasma Turbulence", which was a replacement for a paper with the same title by Dr. Nambu, a Japanese. He discussed extensively the application of Kirchoff's emission law in turbulent plasmas, and described the conditions under which a turbulent plasma can be optically thick at the electron cyclotron frequency. An interesting aspect of this talk is that Tsytovich referred to a gamma-ray laser which he called the GASER (Gaze-er). This is the first time I heard anyone mention this acronym, or the gamma-ray laser. The connection between the gamma-ray laser and his talk on plasma turbulence was not at all clear, although he did seem to imply that plasma turbulence was somehow involved in the gamma-ray laser, as if somehow an energetic, turbulent plasma could be stimulated to act like a laser at gamma-ray frequencies.

On the last day of the conference, a Japanese, Yamanaka, spoke on inertial confinement fusion, and described laser fusion research underway at Osaka, Japan. He described some pellet configurations that I had not seen discussed before, including what he called the foam and double-shell targets. The foam target consists of a DT pellet at the center surrounded by an annular shell of foam material, the function of which apparently was to rapidly ionize and absorb the laser radiation. The double shell foam target consists of a DT pellet at the center surrounded by an annular shell of foam, and then an outer hard shell outside the foam. He also described something called the "cannonball" model which was a double shell target with a hole in the outer shell. The laser radiation apparently comes in through the hole in the outer shell, and reflects in the annular cavity. He claimed a six-times enhancement of the compression over a uniformly compressed target. He claimed to have gotten pressures of 30 megabars in these experiments.

REPORT ON THE SYMPOSIUM ON NEW TRENDS IN UNCONVENTIONAL APPROACHES TO MAGNETIC FUSION

This symposium was organized by Bo Lehnert of the Royal Institute of Technology in Stockholm Sweden, and took place on June 16-18, 1982. Its timing was arranged to dovetail with the Goteborg conference. Eighty-three individuals attended this conference. There were 27 papers with no simultaneous sessions. I had a paper on the program entitled "Ion Heating and Containment in an Electric Field Bumpy Torus (EFBT) Plasma". This paper summarized work on the EFBT concept which I had done at NASA Lewis.

This conference was not well advertised in the United States, and so the program and attendance was dominated by Europeans who were interested in so-called "unconventional" approaches. Here in the United States, the stellarator/torsatron group at Wisconsin, the Topolotron group at Brigham Young University, the Tormac group at Berkeley, the Linus effort at the Naval Research Laboratory, and several others were not represented on the program. Most of these papers were neither new nor unconventional. Many of the papers were concerned with various types of pinches, including reversed field pinches, field reversed theta pinches, theta pinches, Z-pinches, and other variations of the basic pinch concept. There seemed to be little concern that these concepts would make poor fusion reactors from an engineering point of view. Except for my own paper and that of Quinn, no one discussed the engineering requirements that need to be placed on advanced fusion reactors. I was very pleased with the reception of my own paper on the EFBT concept. Sixty copies of the paper were picked up from the registration desk, and I had several interested questions after my presentation. The proceedings of this Symposium are going to appear as a separate issue of the Journal of Nuclear Instruments and Methods sometime during the next year.

An invited paper on the reversed field pinch was given by H. A. D. Bodin of the Culham Laboratory, who is a pioneer in this general area. The reversed field pinch (RFP) goes back to the old ZETA experiment operated at Harwell in the late 1950's. In RFP's, the toroidal and poloidal components of the magnetic field are of comparable strength (unlike tokamaks, where the toroidal field is about a factor of 10 stronger), and in the outer regions of the plasma the toroidal magnetic field has the opposite direction (ie. is reversed) with respect to the magnetic field on the axis. The RFP radial equilibrium is produced by the plasma itself, which sustains the required RFP configuration by a process known as self-reversal. Since the current in RFP's can exceed the Kruskal-Shafranov limit, there is powerful ohmic heating. Because of the high shear of the magnetic field lines along the radius, confinement at high beta may be possible. In the RFP, the current does not flow around the major circumference of the containment volume like a simple single-turn loop; the current configuration actually looks like a thick rope wound around the magnetic axis in a helical spiral.

In RFP's an important parameter is the ratio of the total plasma current to the number density of the plasma. When this parameter is high, the plasmas of RFP's are plagued by impurities and have a high Z_{eff}. The scaling of the energy containment time is not neoclassical but under characteristic operating conditions the energy containment time in RFP's is approximately 10% of the classical energy containment time. These energy containment times are approximately 1/10 to 1/50th of the energy containment times predicted by Alcator scaling. Typical values of the energy containment time in RFP's range from 30 to 300 microseconds, and values of the plasma stability index beta are typically 10%. At this stage of RFP research it is not clear what physical process limits the value of beta, but it seems that values of beta up to 25% may be possible with larger devices.

The Ohmically Heated Toroidal Experiment (OHTE), one version of which is in operation at General Atomic in San Diego, is a cross between the stellarator and the reversed field pinch. The pulse lengths of OHTE experiments range from 1 to 10 milliseconds, with a value of the plasma stability index beta that is typically 10%. Number densities are in the range of 1 to 10 x 10^{13} particles per cubic centimeter. Although there are about 5 OHTE experiments currently in operation, we heard in detail about the one from General Atomic. They claimed to have achieved a plasma with minimal impurities, and a Z_{eff} of approximately unity. The plasma stability index for the poloidal field component was about 30% for the OHTE experiment, and only about 10% when this experiment was operated in the RFP configuration.

Harold Furth presented an invited paper on Compact Tori, nearly all of which was devoted to the spheromak configuration. He distinguished between the field reversed theta pinch, in which the toroidal magnetic field is zero, and the spheromak configuration in which a strong poloidal magnetic field is assisted by a toroidal magnetic field in the plasma. The spheromak is a freely moving plasma blob of a kind originally developed by Wells, although Furth did not give Wells credit during his talk. The spheromak plasmas should be stable for extended periods of time, and may be related to the phenomenon of ball lightning, which, in some instances, has been observed to be stable for periods of 30 seconds or more.

They have conducted a series of preliminary experiments at Princeton which generated small spheromak plasmas. They are currently building the S-1 experiment, which was preceeded by the proto S1,-S2-S3, which operated with slightly different magnetic field configurations. At Princeton, they expect the average beta in spheromak plasmas to range between 5 and 10%, and they feel that spheromak plasmas may be capable of values of beta as high as 30 or 40%. The spheromak concept has serious defects from an engineering point of view, including the pulsed or cyclic nature of the plasma, and the rather small size to which the spheromak plasmas appear to be limited. However, Furth made the point that the magnetic field at the coils generating the spheromak plasma is less than the magnetic field within the plasma itself. This is opposite from a tokamak, where the toroidal magnetic field in the plasma is significantly less than the magnetic field in the coils.

I presented a paper for George Miley on "Conmpact Tori for Alternate Fuel Fusion", since George could not make the conference due to a personal emergency. George made the assumption that a reversed field theta pinch could be operated in the steady-state by neutral beam injection and a form of current drive, then proceeded to examine some of the engineering implications of the reversed field theta pinch. George Miley has been an advocate of the reversed field theta pinch for several years, even at a time when workers at the Los Alamos National Laboratory were not taking him seriously. George Miley concluded that a reversed field theta pinch should make an attractive engineering test facility for advanced fusion fuel cycles. Such a facility would generate only a few tens of megawatts, while still providing fluences and other fusion burn conditions appropriate to reactor conditions.

A paper by W. E. Quinn from Los Alamos described their experimental work on compact toroids, which includes the CTX facility (compact toroidal experiment). They use a coaxial plasma gun to produce the compact toroid, and they observed the magnetic reconnection which leads to the separation of the compact toroid from the coaxial source. The compact toroid is characterized by an electron density of 2 to 4 x 10^{14} particles per cubic centimeter, an electron temperature of 10 eV, a peak magnetic field trapped in the plasma of 6 kilogauss, and total configuration lifetimes up to about 0.7 millisecond. They also have a second facility, the Field Reversed Configuration (FRC) which is a high beta, axisymmetric compact toroid that is prolate i.e. stretched out along the axis of the plasma. In this device, the containment times are on the order of .1 milliseconds, the electron number densities from 2 to 5 x 10^{15} particles per cubic centimeter, electron temperatures are 200 to 500 electron volts, and the value of the plasma stability index, beta, about .7 to 1.0.

One of the newest and most interesting of the experiments reported at this meeting was the "Rotamak" experiment, which is being operated at the Flinders University of South Australia. This configuration consists of a plasma confined by a strong vertical magnetic field. Superimposed on this is a transverse magnetic field which rotates in a plane normal to the vertical magnetic field. Typical rotational velocities are on the order of several hundred kilohertz. The values of beta achieved in this experiment approach unity, with confinement times that so far are relatively low, on the order of a few 10's of microseconds. The electron number densities of this plasma have been as high as 10^{14} particles per cubic centimeter. Most of the limitations of the parameters reported in this paper are clearly the result of the rather small scale of the experiment, and the investigators are quite confident that more interesting results will be possible when the experiment is scaled up.

Professor Arnulf Schluter from Garching, West Germany, gave an invited talk on advanced stellarators. He has been one of the leading advocates in Europe of the stellarator configuration, and has worked closely with the Wendelstein VII experiment at Garching, which is currently the world's largest stellarator experiment. They have achieved a plasma stability index beta of 1% in their plasmas, and he feels that stellarators should be capable of operating with betas as high as 5%. They are currently building a scaled-up version of the Wedelstein VII experiment, which will use existing toroidal field coils, but will not have the usual helical stellarator windings wrapped around the containment volume. Instead of these helical windings, the Wendelstein 7-AS experiment will have modular, twisted coils, which will generate the same magnetic field configuration as an ℓ = 3 helical winding, but which can be removed independently and do not contain conductors that thread the toroidal field coils. This will be a major experiment, and they intend to apply ion cyclotron heating, neutral beam injection, electron cyclotron resonance heating, and ohmic heating to the new version. They have looked at a fusion reactor scale-up of this device, which would have a beta somewhat under 5%. The

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stellarator is capable of operating in the steady-state, unlike the classical tokamak, but the beta limitation means that from a practical engineering point of view it cannot be used to burn advanced fusion fuels.

A very impressive paper was presented by Professor Koji Uo from Kyoto University in Japan. The eliotron-E is an $\ell = 2$ torsatron configuration made up of modular field coils which produce a plasma with an elliptical cross-section. This experiment is also a very large one. The modular coils are water-cooled copper, the major radius of the experiment is 2.2 meters, and the minor radii of the plasma is 21 and 40 centimeters, since the plasma cross section is elliptical. The toroidal magnetic field of this experiment is 2 Telsa. Professor Uo presented a very impressive set of diagnostic data, much more extensive and complete even than major tokamak experiments in the West, which showed time histories of radial profiles of various plasma parameters. The particle and energy containment times achieved in this configuration are impressive. The electron energy containment time has been up to 35 milliseconds, and the Lawson parameter (ie the product of density and energy containment time) has been has high as 2.5×10^{12} seconds per cubic centimeter. The ion kinetic temperatures during neutral beam injection have been up to 660 electron volts, with about 500 electron volts of this kinetic temperature being due to the neutral beam heating. They have seen no sign of saturation of the ion kinetic temperature as a function of the input power. The number densities are typically 3×10^{13} electrons per cubic centimeter and the particle containment time has been as high as 70 milliseconds. They have injected up to 1.3 megawatts of neutral beam power in this experiment and Professor Uo expects that the plasma stability index may be as high as 5% in reactor-sized devices. This device should in principle be capable of operating in the steady-state, but it was disappointing that, like tokamaks and stellarators, its stability is apparently limited to betas of no more than about 5%.

There were several papers on Z-pinches from the Los Alamos National Laboratory, Japan, and the Imperial College of Science and Technology in London. The Z-pinches are high density experiments, which involve as much as 10 million amperes of current flowing along the axis of the discharge. This current generates a self magnetic field which pinches the plasma to a small diameter. The electron number densities range from 5×10^{19} to 10^{21} particles per cubic centimeter. The duration of these experiments is extremely short, and while they are a useful test bed for high density plasma physics, it is not at all clear how they can be translated into a reactor that is efficient and feasible from an engineering point of view. This feasibility problem was not addressed in any of the papers at this conference.

A paper was presented by S. C. Prager of the University of Wisconsin on high beta multipoles. This configuration is generated by four levitated rings inside a toroidal chamber with an approximately square minor cross section. The plasma is confined mostly in the region between the four conducting rings which are spaced in the shape of a square in the minor toroidal cross section. This approach is one which will almost certainly not lead to a power producing reactor because of the necessity of having the levitated rings in the containment volume. Such rings would be heated or destroyed by the power flux from a reactor plasma. Nonetheless, Prager made the point that multipoles are useful because neoclassical theory is virtually identical in all symmetric toroids including tokamaks, spheromaks and multipoles. They observed the so called Bootstrap current which arises from the diffusion of particles across the magnetic field. The bootstrap current occurs along the magnetic field. They claimed that their measurements agree with neoclassical theory. These multipoles are capable of very high beta, and they have experimentally observed values of beta ranging from 11% to 44% at a characteristic location in their containment volume. The value of beta of 11% is consistent with MHD stability theory, but the higher limits, 44%, are claimed to be above these predicted by MHD instability theory.

John Dawson of UCLA gave an interesting paper on a toroidal confinement experiment which features direct ohmic heating of the ions. This is a toroidal version of the picket fence concept, in which the magnetic field is generated by magnetic polepices on the wall of the containment vessel, and the magnetic field lines then bow inward toward the toroidal containment vessel. The plasma is established in the low magnetic field region. Since the device is toroidal the electrons tend to be trapped on magnetic field lines. When an ohmic heating current is driven by transformer action, the induced current is carried by the ions, since they are not trapped on the magnetic field lines. They found that a toroidal ion current of 3 to 6 thousand amperes results, and they verified that the current is carried by the ions. The ion temperatures are 40 to 110 eV in a plasma with a density of about 10^{13} particles per cubic centimeter. The electron temperature is lower and is generally in the range of 20 to 40 electron volts. The beta of the plasma high, about 20 to 30%. This is a rather interesting device, since the magnetic field is stronger at the coils than it is in the containment volume. This is also an attractive possibility for advanced fuel cycles, which may be operated at high kinetic temperatures where synchrotron radiation from hot electrons can be a problem in strong magnetic fields. They proposed to build a larger device with a major radius of 90 centimeters, a minor plasma radius of 30 centimeters, a magnetic field of 1 tesla at the cusps on the wall. They expect in this device to get an ion kinetic temperature of 1 keV.

Al Wong of UCLA gave a paper on "Surface Magnetic Confinement in Toroidal and Linear Mirror Systems." These devices also have magnetic poles generated by electromagnets or permanent magnets on the wall of the vacuum vessel, which form a magnetic field configuration weak at the center of the containment volume and which increases as one approaches the walls. In one of these devices they achieved a particle containment time of about 100 milliseconds, and a Lawson parameter as high as 7×10^{10} seconds per cubic centimeter. At UCLA, they recently built a new device called LAMEX (Large Axisymmetric Mirror Experiment) in which the parameters span the range 10^9 to 10^{13} particles per cubic centimeter and ion temperatures from 1 to 100 electron volts. They conducted experiments to determine the mirror ratio scaling. It appears that the containment time varies at least linearly with mirror ratio, the ratio of maximum to minimum magnetic fields in this device, rather than with the logarithm of the mirror ratio, as is the case with 90° scattering collisions.

There was a very interesting paper by D. D. Ryutov from the Institute of Nuclear Physics in Novosibirsk, USSR. The mirror research at Novosibirsk does not often get published in the literature. In this invited paper, Ryutov described the work at his Institute, one major thread of which is research on simple axisymmetric magnetic mirrors. He seemed to advocate the use of simple magnetic mirrors, rather than tandem mirrors. Ryutov seemed to feel that the tandem mirror concept had at least two important defects. He expected that microinstabilities would result in fast scattering of confined particles into the escape cone, and he felt that there was an unacceptable constraint on the allowable level of microfluctuations, since such fluctuations would lead to loss in the escape cone. This was a rather interesting point of view since the tandem mirror concept originated in Russia. He described a series of rotating plasma experiments, similar to the old Burnout-V experiments which were operated at Oak Ridge. These are based on a device simialr to the modified Penning discharge, in which a strong magnetic mirror provides gross confinement, and the plasma is biased with electrodes at either end so that a strong radial electric field points radially outward. This leads to $\bar{E} \times \bar{B}/B^2$ rotation of the plasma. The centrifugal force thus produced improves the longitudinal confinement.

He made the interesting statement that the E/B drift velocity should be about 2 to 3 times the ion thermal velocity. I'm not sure why he thought so, since in my own work I showed that the drift velocity and the thermal velocity are comparable in a modified Penning discharge. The number densities that have been achieved are on
ticles per cubic centimeter in the PSP-I device, which operated over 1971-1979. This had a pulse duration of 10 milliseconds. Ion kinetic temperatures of 1 keV were observed, with electron kinetic temperatures of 20 eV. This large ratio between ion and electron kinetic temperatures is a result of both species achieving essentially the same drift velocity, so that their energies tend to be proportional to the masses. The magnetic mirror had 1 tesla in the magnetic mirror throats, and a 2 1/2 to 1 mirror ratio. They followed the PSP-1 device with a second, huge upgrade of it, the PSP-II, which was built one year ago and has just recently gone into operation. This machine is about 4 meters high and 15 meters long. The maximum magnetic field is 7.2 tesla, and it has a 2.5 to 1 mirror ratio.

In addition, Ryutov described some work with electrostatically plugged cusps, a very old idea which the Russians are still pursuing, and which they regard in many ways better than the tandem mirror since the electric fields are externally imposed. He cited as the main problem the large size of the so called "point cusps" at the magnetic field maximum, and the difficulty in blocking the cusps with electric fields imposed by electrodes.

In addition to the above experiments at Ryutov's Institute, they are also building the GOL-3 experiment, which is a multiple-mirror experiment with 30 individual magnetic mirrors in a linear array. One would think that they would have been better off to have made these into a bumpy torus, but the principle of operation of this device is that the individual magnetic mirrors are to have a mean free path for scattering into the escape cone that is comparable to the length of the individual mirrors. Under these circumstances, an ion which scatters into the escape cone in one of the central mirrors will have a high probability of being scattered back into the confinement region of velcity space when it traverses one of the other mirrors. This is a larger and scaled up version of the multiple mirror system that was operated at Berkeley.

I have the conference Proceedings, but not as yet the full length papers, available in my office for anyone who wishes further information.

VISIT TO JET/CULHAM JUNE 21, 1982

On my way back to the United States, I stopped at the Culham Laboratory to visit with John Butterworth and his collegues in the Fusion Technology Group. While there, I also saw the JET experiment, which is in the final stages of assembly. I was suprised to find that fusion technology, as we understand it in this country, is very little emphasized at Culham. The Institute for Plasma Physics at Garching, West Germany appears to be the European lead center for fusion technology. This lack of emphasis at the Culham Laboratory was attributed to the fact that the previous director was a physicist, and not particularly interested in fusion technology. It is felt that that situation may change, since the current Director of Culham has a solid state physics background, and is well aware of the materials and other engineering problems facing the fusion community. I gave a seminar presentation on my recent work on wall loading limits and economic constraints on advanced fuel fusion reactors, and this seemed to be well received. In Culham, as in Europe generally, there seems to have been little thought or attention given to the needs of the electric utilities, to the constraints on fusion power imposed by enginering considerations, or to the advantages or disadvantages of advanced fusion fuel cycles relative to the DT reaction.

The JET (Joint European Torus) was very impressive. The original design of this experiment started in 1973, when a consensus among the fusion research laboratories in Europe was reached that the next step in fusion research was too large for any one European country to support it alone, and that this experiment would have to be a combined European effort. It was further agreed that the device should be a tokamak, although the politicians insisted that it be called a torus and not a tokamak, in case some other magnetic field configuration should prove more desirable from a technical point of view. The design team which produced the tokamak was convened as early as 1974, and was headed up by Rebut, the French engineer who built the successful TFR tokamak at Fontenay-Aux-Roses which went into operation in March of 1973. Because of his involvement as head of the design team, it is no coincidence that the technology of JET very closely resembles that of the TFR tokamak, and is fundamentally unlike the technology of the DITE or CLEO experiments at Culham. The latter, for example, use liquid nitrogen temperature toroidal field coils. The JET project encountered delay between 1975 and 1977, during which time the design team almost disbanded. This delay was almost solely on the single issue of siting the experiment. The European Council of Ministers appointed an advisory committee consisting of senior scientists from various European labs and asked them for recommendations on several points, including siting the people who were technically qualified, however, refused to give the politicians a recommendation on which site should be chosen.

The politicians temporized for 2 years until a consensus emerged that the experiment should be sited at the Culham laboratory in England. National sensitivities required quite a bit of horse-trading among the various countries supporting this experiment. The site is located in England, the head of the design team is a Frenchman, and the man responsible for building the JET experiment itself, Hans-Otto Wuster, is a German. Moreover, it was agreed at the time JET was sited at Culham that any successor to it would not be located in England. The JET experiment was a precedentsetting effort of scientific cooperation for the common market countries, and the political aspects of this have been summarized in a book by Denis Willson, entitled "A European Experiment". It makes interesting reading for anyone involved in the management of scientific experiments.

One aspect of the JET experiment is that the scientists responsible for it seem to have gotten away with murder in terms of setting themselves easily achieved goals for the operation of the experiment. Achieving scientific breakeven or any other form of fusion energy breakeven is not one of the goals of this experiment, and hence they feel free to operate the JET device with ordinary hydrogen from its inception in mid-1983, until sometime in 1988 or beyond. Only at that time will they burn deuterium and tritium. There is no requirement that the fusion power produced be equal to the input power, or any other number. The goals of the JET experiment are rather vague; they are that the device will extend the parameter range of tokamaks, that the scaling of plasma parameters will be tested, that the technology of operating large fusion experiments will be developed, and so forth. The formal goals of the experiment look easy to achieve and may be achieved very soon after the experiment is first turned on.

The JET experiment is housed in a separate part of the Culham Laboratory with its own shops, office building, motor-generater hall, etc. The office buildings and working environment is superb. The European politicians apparently did not quibble about the funding of the buildings. The lounges, conference rooms, individual offices, and beautifully landscaped gardens will be very attractive to staff from all over Europe. The control room of the JET is very advanced from a human factors point of view. It was pointed out that there are no buttons to push or knobs to turn anywhere in the control room. All of the control functions will be handled by typewriter keyboards and interactive video displays.

The JET apparatus itself is located in the "torus hall" which is a huge structure with concrete walls about 3 meters thick, to shield against the production of neutrons. The entire structure will be operated as a containment vessel at a slightly negative pressure, to contain any tritium. At one end of the torus hall is the assembly hall, which is not a hot cell. There is an intermediate room between the experimental bay and the assembly hall with 3 meter thick doors on it which can serve as a hot cell for the dissassembly of any components that are activated in the experiment. The cross section of the JET plasma is very large, and D-shaped. The aspect ratio is relatively small, about 2.5 to 1. All together, the JET is much larger, and appears to be much better engineered than the TFTR at Princeton. Moreover, the JET seems to have been designed with a sounder sense of physics priorities. For example, the JET experiment will be capable of operating between 20 and 30 seconds at maximum magnetic field, whereas the TFTR experiment was designed with such limited magnetic field capability that it can operate only 1/2 second at maximum magnetic field. The longer containment times possible in the JET experiment could make a very significant difference, if the containment times for either particles or energy scale up to be longer than a few seconds. Also, the long pulse times possible in JET may make it possible to examine the scaling of the ohmic heating decay time, which may not be equal to the value suggested by Spitzer conductivity, but something more rapid, due to anomalous resistivity.

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M E M O R A N D U M

TO: Thomas A. Bryant, Administrative Contracting Officer

FROM: J. Reece Roth, Principal Investigator, Contract N00014-80-C-0063

DATE: 24 May 1982

SUBJECT: Trip report on IEEE International Conference on Plasma Science, Ottawa, Canada

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I attended the International Conference on Plasma Science, held May 17-19, 1932 in Ottawa, Canada. I presented two papers which were supported in part by ONR contract N00014-80-C-0063. Abstracts of these two papers are attached to this trip report, and I can provide copies of the slides used in the presentation (both were oral rather than poster papers) to those who are interested.

Among the co-sponsors for this conference were Carleton University and the National Research Council of Canada. There were approximately 400 papers presented at this meeting, and the number of registrants was more than 500. Most of the attendees were housed in the Carleton University dormitories, and the classroom facilities of the University were used for oral and poster sessions. Like previous conferences in this series, this conference spanned an unusually wide range of applied plasma-related topics. There were several sessions on laser-plasma interactions, intense electron and ion beams, magnetic fusion, commercial arcs and lighting devices, plasma diagnostics, and basic plasma physics research. Perhaps because the conference was held in Canada this year, there was an unusually large representation of overseas authors, particularly from Japan and Latin America.

One of the most active topics at this meeting was high power microwave and submillimeter wave generation, where a number of national laboratories and universities are working, on gyrotrons. Prof. Igor Alexeff of UTK presented a paper on his millimeter "Orbitron" microwave emitter, which attracted a great deal of attention, since it was one of the few new approaches to generating such radiation. This device creates millimeter microwave emission from electrons radiating as they spiral in toward a positively charged wire. They have successfully streched the pulse length of microwave radiation from this device from 20 microseconds to 5 milliseconds.

Thomas Bryant
24 May 1982
Memo
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A new area which appeared at this conference for the first time, was rail guns and mass accelerators. This session was chaired by William Kerslake of the NASA Lewis Research Center in Cleveland, Ohio, and the results of several recent experiments were reported. It seems that the acceleration of projectiles to very high velocities is of interest in at least three distinct areas. The military are interested in projectiles ranging from 10 grams to 10's of kilograms and velocities up to approximately 4 kilometers per second. According to Kerslake, NASA is interested in the electromagnetic launching of tons of matter (he suggested nuclear waste as a possible payload) to velocities comparable to escape velocity from the earth, 20 kilometers per second. A third area in which mass accelerators can find application is fusion research, where fusion grade plasmas must be refueled with pellets of deuterium and/or tritium weighing on the order of 1 to several grams, and which need to be accelerated to velocities between 1 and 10 kilometers per second, in order to carry the neutral fuel to the center of a burning fusion plasma.

Apparently a key result in this area is the Rashleigh-Marshall experiment in Australia, in which three grams were accelerated to a velocity of 5.9 kilometers per second, by a rail gun in which the acceleration was on the order of 600,000 gravities. Also at this session, the first fruits of an experiment at the Westinghouse Research Labs in Pittsburgh were reported. This experiment consists of a 17.5 megajoule homopolar generator set, which can provide 103 volts and up to 2.1 megaamperes to a rail gun configuration which can operate either with a plasma arc or a solid armature. That experiment has produced accelerations of 2.36×10^5 Gs, and while using a solid armature, has accelerated 300 grams to a velocity of 3, and 4.2 kilometers per second, in two initial experiments.

There was a sense of excitement at this session because these initial experiments appeared to demonstrate that the attainment of such very high projectile velocities was possible, and also because it appeared that this approach would meet a perceived need for high velocity projectiles in the fields of space, military, and fusion energy.

The session on plasma waves, instabilities, and antennas in which I presented my work had a number of interesting papers, including two invited Canadian papers relating to plasma experiments in space, and the propagation of plasma waves and instabilities in the magnetosphere. My paper on a paired comparison of high frequency rf emission from two configurations of electric field dominated plasma attracted interest, particularly my observation that the rf emission spectrum from the modified Penning discharge, which is being operated for the ONR contract, was capable of producing a white noise spectrum of rf emissions from below 1 megahertz to frequencies in excess of 1 gigahertz. The physical mechanisem of this white noise emission is presently obscure, but the observations in the laboratory have been quite clear. There also was interest in the tentative observation in these experiments that the modified Penning discharge (which has a large axial gradient of magnetic field to simulate magnetospheric plasmas) appears to have relatively large longitudinal as well as transverse electric fields, on the order of tens to hundreds of volts per centimeter, while the classical Penning discharge operated under our AFOSR contract, appears to have, relatively, much lower longitudinal magnetic fields as a result of the uniform axial magnetic field strength.

In the controlled fusion area, there were a number of interesting new results, particularly from the German Wendelstein VII Stellarator experiment, and from the EBT-S experiment at Oak Ridge. It seems that the confinement properties of the Wendelstein VII Stellarator are superior to those of a Tokamak of comparable dimensions and magnetic field strength. In the EBT-S experiment, recent observations of 20 kilowatts of ICRH heating have resulted in significant increases in the number density (a factor of 2) and ion kinetic temperature (about 40% higher) in the relativistic hot electron rings which are thought to stabilize the plasma. These observations call into serious question the current theoretical understanding of the scaling of EBT plasmas. It is clear from these data that the hot electrons are not being lost by nonadiabatic effects (otherwise an increase in electron kinetic temperature would not lead to an increase in number density), and therefore renders invalid the nonadiabatic loss scaling arguments which were used to extrapolate from the current EBT-S experiment to the EBT-P and reactor grade plasmas. In addition, these observations are inconsistent with currently understood energy transfer processes, since it is not clear how 20 kilowatts of ICRH power into the ion population can increase the number density and kinetic temperature of the hot electron rings, which are absorbing approximately 200 kilowatts of ECRH power in these experiments.

Another fusion-related area of interest at this meeting was the Canadian tokamak program. The Canadian government has very recently approved a thirty million dollar, five year program to build a tokamak at the Hydro-Quebec Research Institute outside Montreal. This tokamak will be of about the general size and configuration of the ISX tokamak at Oak Ridge, but will be designed with special provisions which may allow continuous operation. They hope to do this by operating the ohmic heating current in an ac manner, and to keep the plasma hot enough and dense enough that they can reverse the ohmic heating current in a periodic manner. The Canadians are hoping, but cannot demonstrate, that the current penetration processes in the plasma will allow them to reverse the ohmic heating current in the plasma without destabilizing the plasma in the process. They are designing the vacuum vessel and ohmic heating coils in such a way that the current reversal will be possible within a few milliseconds. The operation of a tokamak with a periodically reversing ohmic heating current is hoped to be Canada's unique contribution to tokamak research and the world fusion effort. As I remarked to Claude Richard, head of this program at Hydro-Quebec, if this works, they will be heros; if it doesn't work nobody will be surprised.

On Wednesday morning there were a series of papers on plasma focus devices (in conflict with the session on railguns and mass accelerators). Two papers on the subject from Romania were withdrawn because the authors did not show up for the meeting. There was an interesting paper under AFOSR sponsorship by Glenn Gerdin of the University of Illinois who reported a scaling law for the neutron production in a plasma focus device. It was found that the neutron yield scales as the current flowing to the plasma focus raised to the 4.6 power. Apparently in an earlier work, Dr. Gerdin reported charged particle energies resulting from plasma focus heating that exhibited energy distribution functions which were power laws, that is, the number of charged particles in a unit energy interval varied as an inverse high power of the energy. This is just the kind of energy spectrum that is observed in cosmic rays and other astrophysical plasmas where the energies of the particles are extremely high, and apparently due to violent heating processes.

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