N66-20058

(ACCESSION NUMBER)	(THRU)
43	1
(PAGES)	(CODE)
CR 70802	25
(NASA CR OR TMX OR AD NUMBER)	(CATEGORY)

FACILITY FORM 602

AVCO EVERETT RESEARCH LABORATORY

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GPO PRICE $ ______

CFSTI PRICE(S) $ ______

Hard copy (HC) 2.00

Microfiche (MF) .50

ff 653 July 65

FINAL PROGRESS REPORT

Contract No. NASw-1101
January 1966

prepared for

HEADQUARTERS
L AERONAUTICS AND SPACE ADMINISTRATION
OF ADVANCED RESEARCH AND TECHNOLOGY
Washington, D. C.

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I. INTRODUCTION

Although this report is the final report due under Contract NASw-1101, work on the Plasma Radiation Shielding concept is by no means concluded. It is expected that work on this topic will continue under a different NASA contract and that related work will continue to be supported by the Air Force.* As in the past the work supported by the Air Force is so closely related to that supported by NASA that this report will describe technical progress without attempting to assign each item to one sponsor or another. Sponsorship of the papers listed in Section IV is clearly indicated.

Technically progress in the area of Plasma Radiation Shielding has been far greater than originally hoped. Several important milestones have been passed, although we are still short of a definite statement on the feasibility of the Plasma Radiation Shielding concept. In view of this position, we will in this report give a brief summary of the work accomplished to date, together with an indication of current research directions.

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*Under AFOSR Contract AF49(638)-1553.

II. GENERAL REVIEW OF PROGRESS

In general, progress has been made as follows:

1) The basic mode of instability appropriate to the electron cloud as envisaged for the Plasma Radiation Shield has been identified. Subject to various qualifications, it has been shown both experimentally and theoretically that this mode can be controlled by an appropriate choice of physical and geometrical parameters.

2) The basic method of electron injection has been demonstrated (at low voltage, and in a simple geometry), and shown to be in agreement with preliminary analysis.

3) Calculations have shown that early estimates of the weight of a Plasma Radiation Shield were reasonably accurate. At present, no further engineering calculations of this kind are justified, but the situation remains under review.

1. Progress in the area of stability has been considerable. The crossed-field experiment illustrated in Fig. 1 was performed, with the results shown in Fig. 2. The interpretation of these results is given in Fig. 3 and amounts to the following: in cylindrical geometries of this type stability of crossed-field electron beams apparently exists whenever the parameter

$$q = \frac{\omega_p^2}{\omega_c^2} = \left[\frac{\text{plasma frequency}}{\text{cyclotron frequency}}\right]^2$$

is less than about .03 . This is a very satisfactory result from the point of view of the Plasma Radiation Shield.

On the theoretical side, a satisfactory explanation of this situation has been achieved. In the first instance the problem of an infinite plane electron beam, as shown in Fig. 4, was treated. The parameter q is left variable. The growth rates for unstable waves propagating across the magnetic field are shown in Fig. 5. The growth rates for short waves vanish in a manner consistent with the experimental evidence just quoted. Long waves are always unstable in the infinite plane geometry, but for geometries in which the electron orbits are periodic, there may not be room for a sufficiently long wave. These ideas are

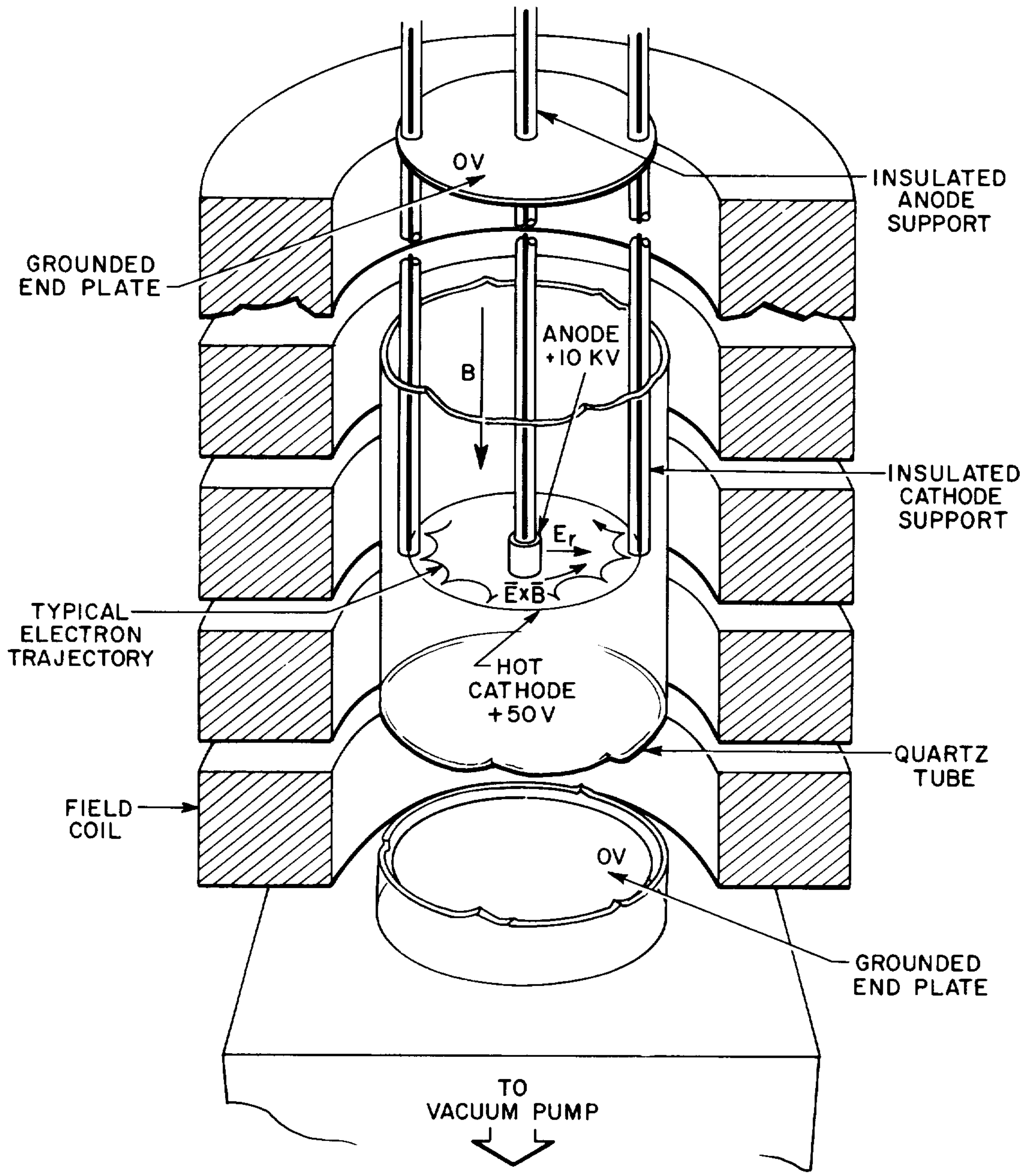

Fig. 1. This steady state inverted magnetron-type experiment was performed with the object of studying the containment of electrons in crossed electric and magnetic fields. The geometry is linear rather than toroidal, and the anode is at the center. Electrons from a space charge limited cathode are attracted to the anode by an applied potential of up to 10 kV. The anode current is then measured as a function of the applied magnetic field. The results are shown in Fig. 2.

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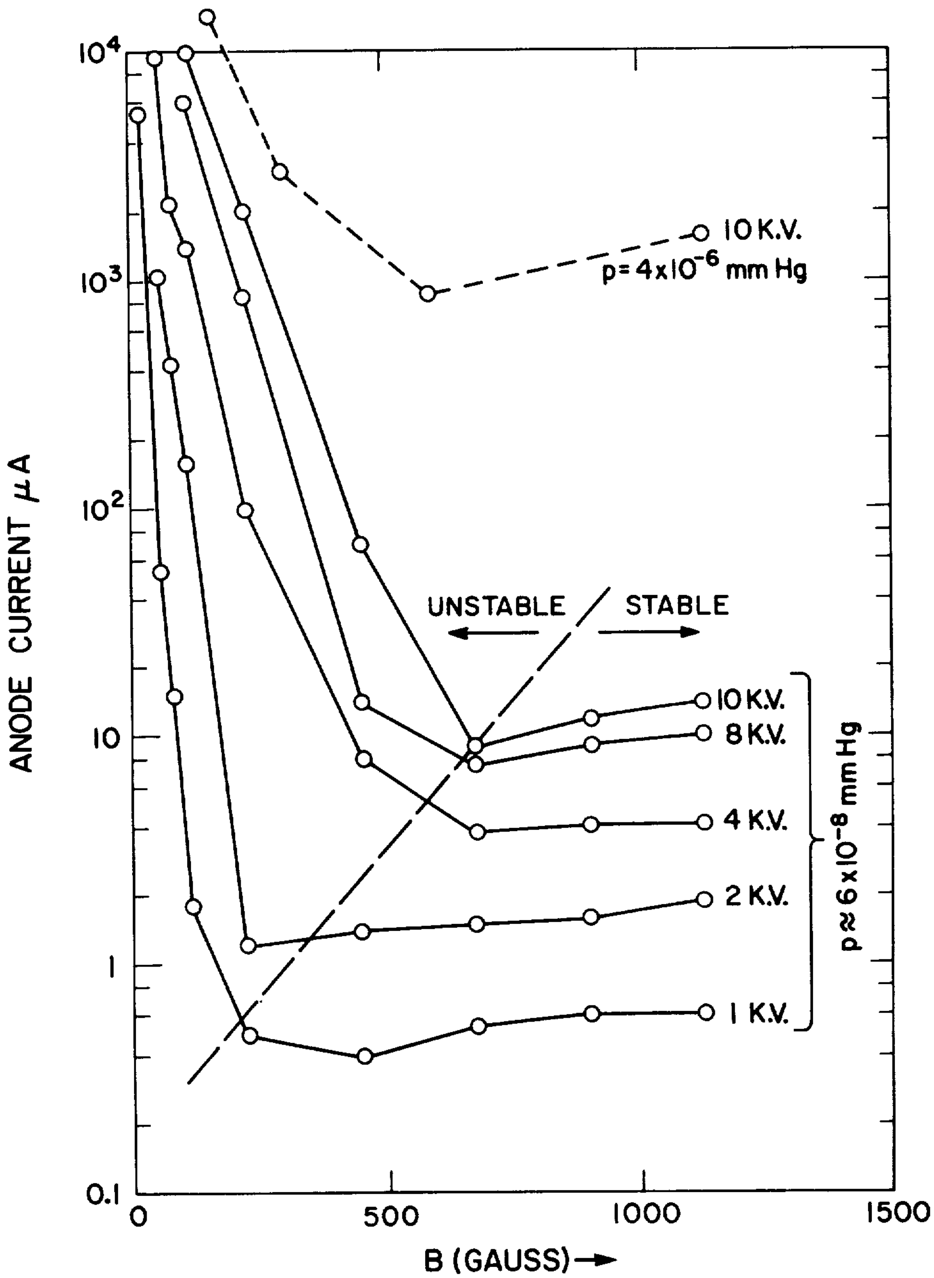

Fig. 2. Current-magnetic field plots for the apparatus of Fig. 1. For low B, large anode currents were drawn and the experiment emitted considerable RF noise. For B larger than a critical value (dashed line) but at the same applied voltage, the current stabilized at a low level, and the experiment became very quiet. The final current scaled linearly with the background pressure indicating that the anode current was principally due to classical diffusion. The interpretation of these results is given in Fig. 3.

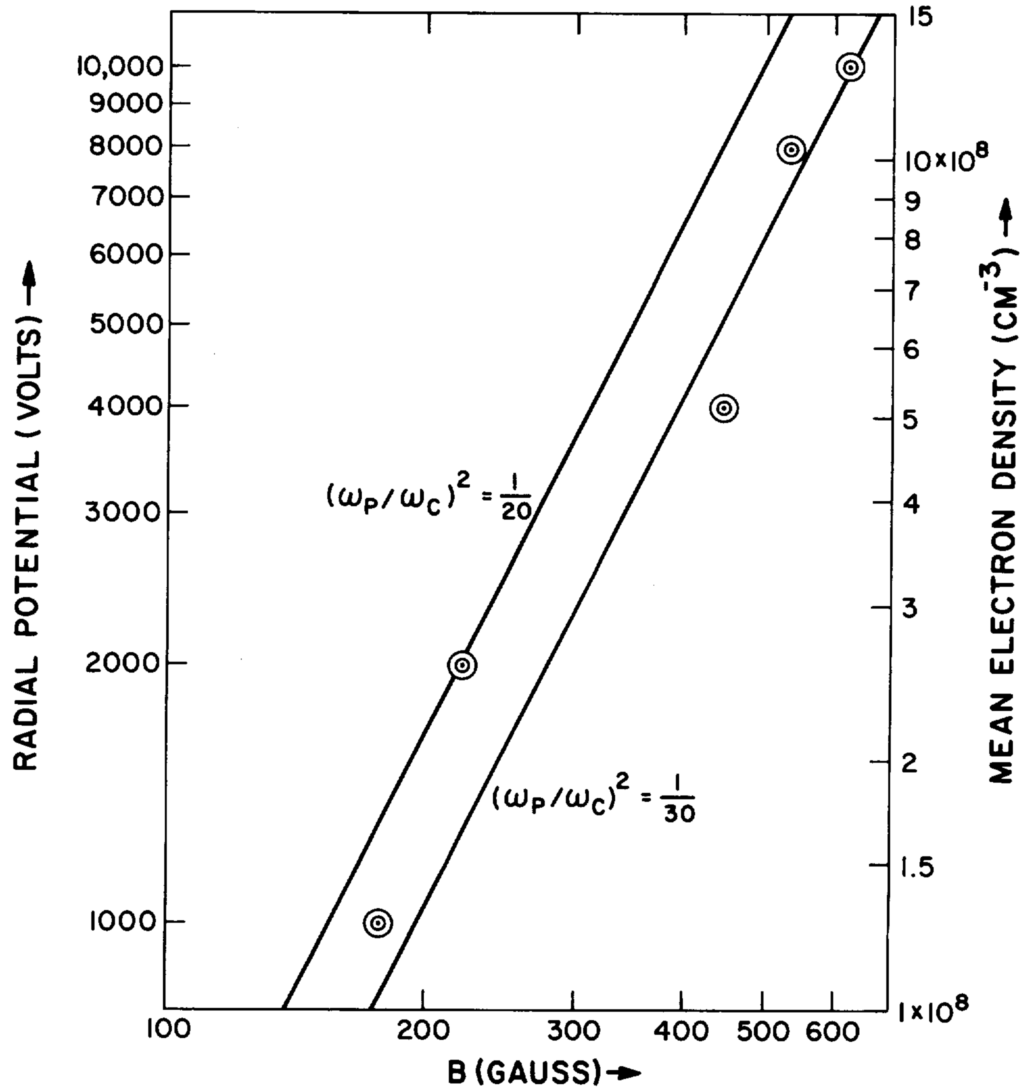

Fig. 3. A cross plot of the critically stable points from Fig. 2. The electron density was estimated from the applied voltage, the dimensions of the system, and the knowledge that the cathode was space charge limited. Evidently stability is present for $q = \omega_p^2/\omega_c^2 \lesssim .05$. A theory exists which explains this phenomenon.

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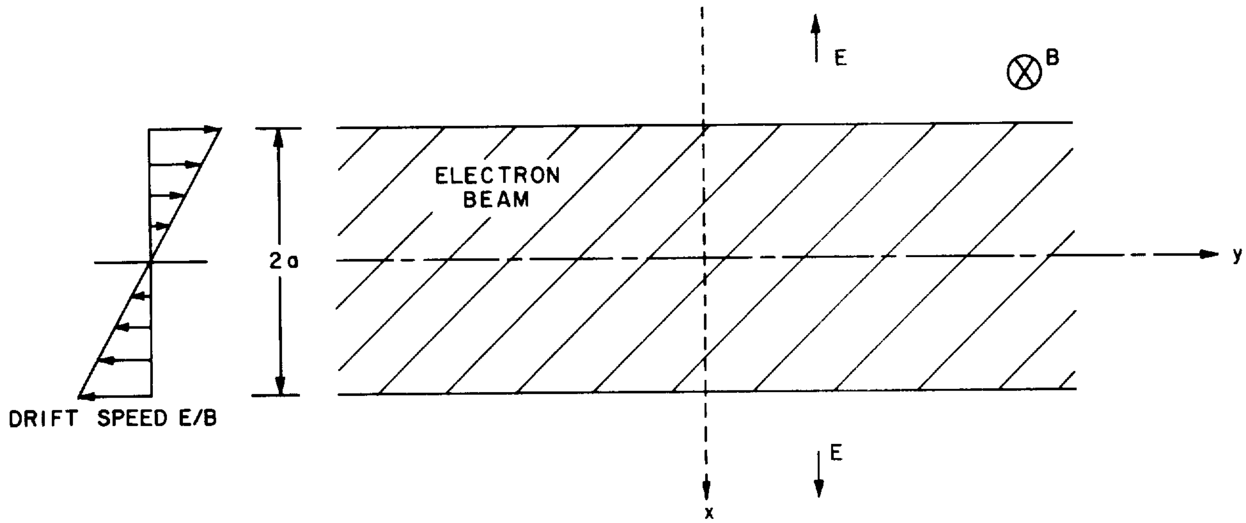

Fig. 4. Illustration of the inherent presence of shear in crossed-field electron beams. Stability calculations were performed for waves traveling in the drift direction and for arbitrary values of $q = \omega_p^2/\omega_c^2$. Dispersion relations for different values of q are given in Fig. 5.

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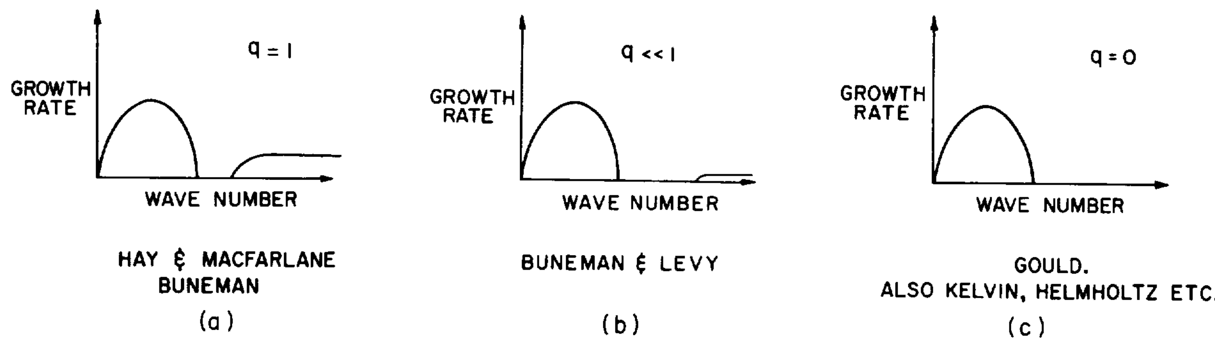

Fig. 5. Schematic diagram of growth rate vs. wave number for waves propagating in the drift direction for the geometry of Fig. 4. The maximum growth rate for the long waves is on the order of $\omega_o = \omega_p^2/\omega_c$. The wave number scale is such that the growth rate for the long waves vanishes for waves whose length is comparable to the beam thickness. For $q\ (= \omega_p^2/\omega_c^2) = 1$ (the magnetron case) growth is predicted for long and for short waves. For $q \ll 1$ (Plasma Radiation Shield case) the growth of the long waves is unaffected, but the growth rate of the short waves is reduced to $\omega_o e^{-2/q}$ - a negligible number for $q \lesssim .05$. In the limit $q = 0$, the short wavelength growth disappears altogether; the instability is then perfectly analogous to the Kelvin-Helmholtz instability of fluid dynamics with ω_o representing the vorticity. For an explanation of how this long wavelength instability is avoided in the Plasma Radiation Shield, see Figs. 6, 7, 8, 9 and 10.

A4039

illustrated in Figs. 6, 7, 8, 9 and 10. So far as it goes, the theoretical and experimental evidence on the problem of stability is in good agreement, and offers as yet no reason to doubt that the Plasma Radiation Shield concept can be made to work.

2. Progress in studying inductive ejection has also been satisfactory as far as it has gone. An apparatus designed specifically for the study of this problem was constructed and has been successfully used. In its original form, it contained an electron gun in its interior, and the outer cylinder of the apparatus (shown in Fig. 11) was silvered so that the magnetic flux that entered the cylindrical interaction space did so uniformly in the azimuthal direction. Results obtained in this apparatus are illustrated in Fig. 12 and were satisfactory, but decidedly limited due to the presence of the electron gun.

The apparatus was later modified as shown in Fig. 13. The outer cylinder is now of stainless steel, but has a narrow slot. All the magnetic flux now enters the interaction space through this slot. Another way of putting this is to say that an electromotive force $\dot{\Phi} = \pi a^2 \dot{B}$ is induced across the slot. In this configuration the injection apparatus begins to resemble the so-called "Kino crossed-field electron gun" which is the basic design underlying magnetron injection guns of all kinds. However, at this stage the resemblance is incomplete because, as shown in Fig. 13, the cathode consists only of a long filament suspended in the magnetic field direction. In the Kino gun a strip of large sectional area is used; such geometries would yield substantially larger currents than our thin filament. Nevertheless, we have been able to explain our results on a basis closely resembling that of Kino. The most important consequence of this situation is that we feel confident that the whole process of injection into our device (or into the Plasma Radiation Shield) can be reduced to quantitative and meaningful analysis of the design factors. This analysis must extend somewhat beyond that of Kino principally because our gun must be designed to operate in magnetic and electric fields that change in time, whereas standard crossed-field guns operate under steady conditions. This will force us into certain design compromises which, at the moment, do not appear to be serious.

Typical results achieved with the gun in the form shown in Fig. 13 are given in Fig. 14. Fig. 15 is a cross-plot of results of the type illustrated in Fig. 14. For each experiment the maximum radial voltage V_R is plotted against the appropriate induced voltage $\dot{\Phi}$ which is essentially the operating voltage of the gun. It can be seen that the relation between V_R and $\dot{\Phi}$ is linear over a range of about 10 in voltage. Thus, we write

$$V_R = M\dot{\Phi}$$

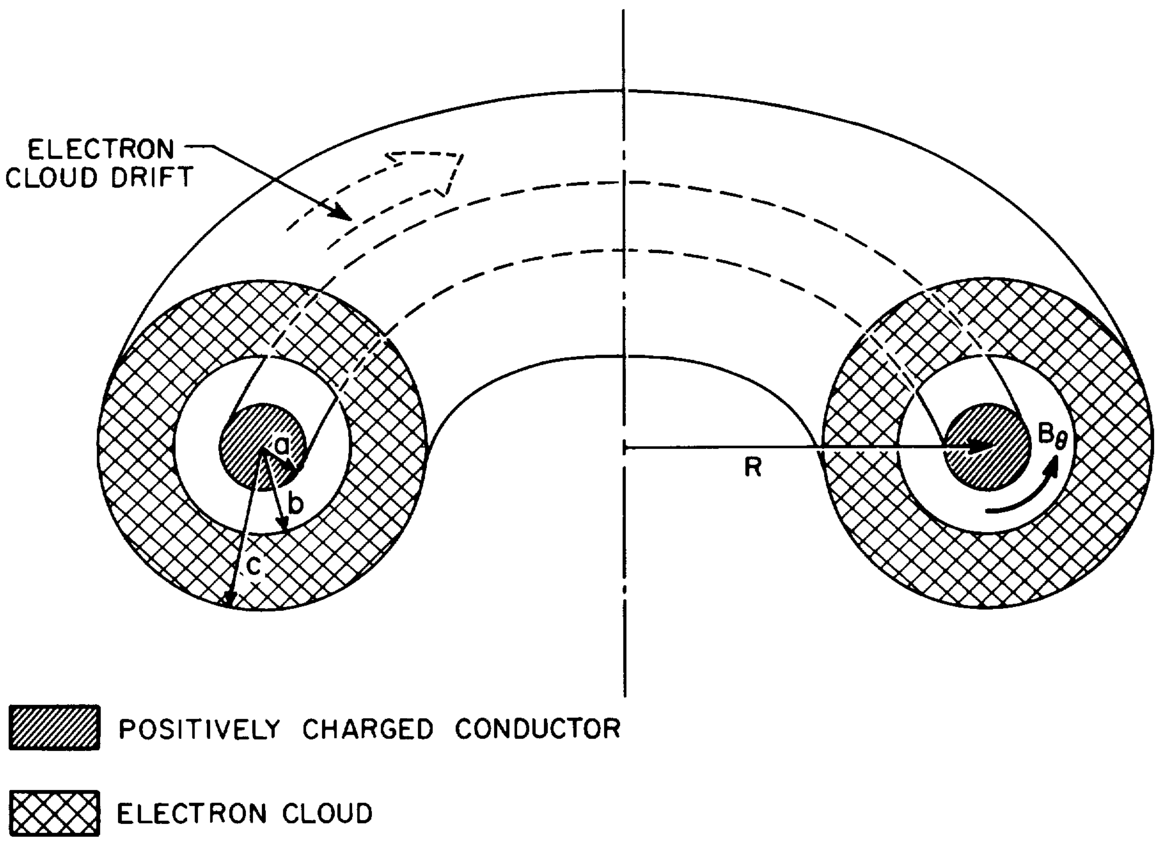

Fig. 6. Assuming $q \ll 1$, the stability of this configuration which closely resembles the Plasma Radiation Shield was studied. A further simplification involved neglecting the curvature of the Plasma Radiation Shield but allowing wavelengths shorter than the perimeter of the device. A cross section of the plane geometry actually analyzed is shown in Fig. 7.

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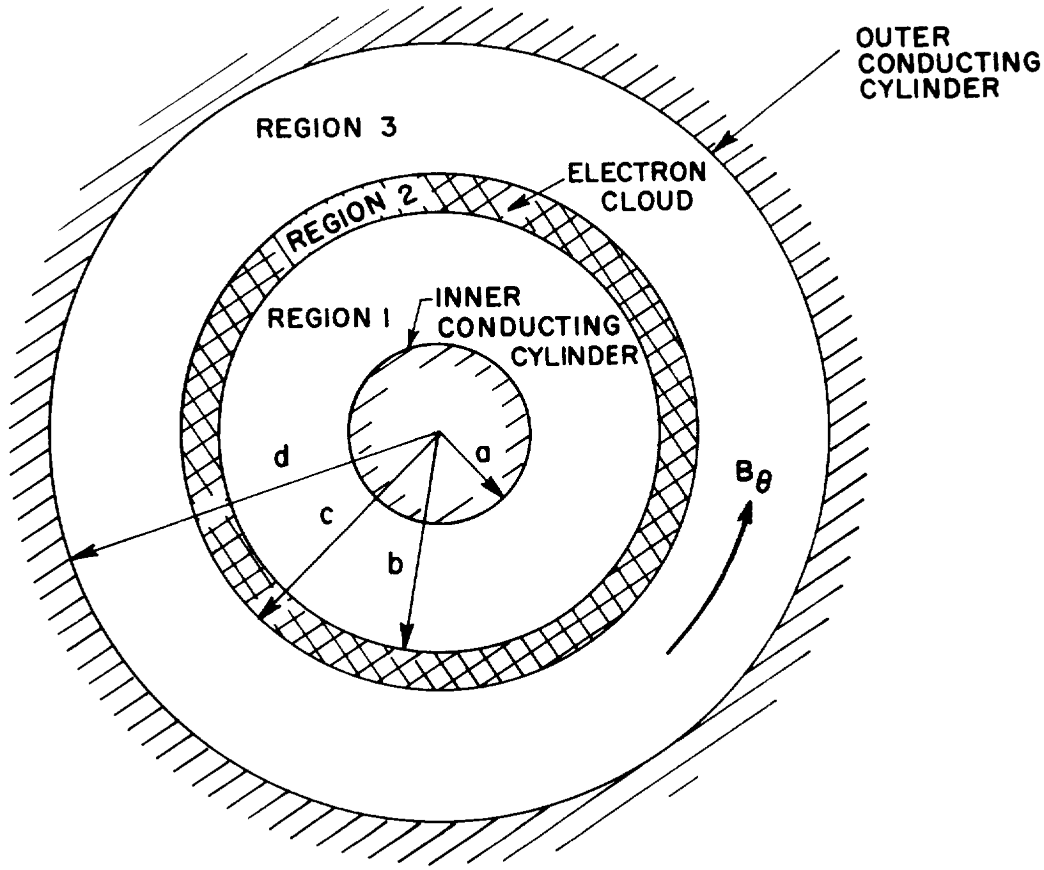

Fig. 7. This is a cross section of a straightened out version of the Plasma Radiation Shield illustration in Fig. 6. The conducting cylinder at radius d is not present in the space device. The azimuthal magnetic field declines inversely with the radius. The electron beam drifts and the waves in question propagate perpendicular to the plane of the paper. The results of calculations based on this geometry are given in Fig. 8.

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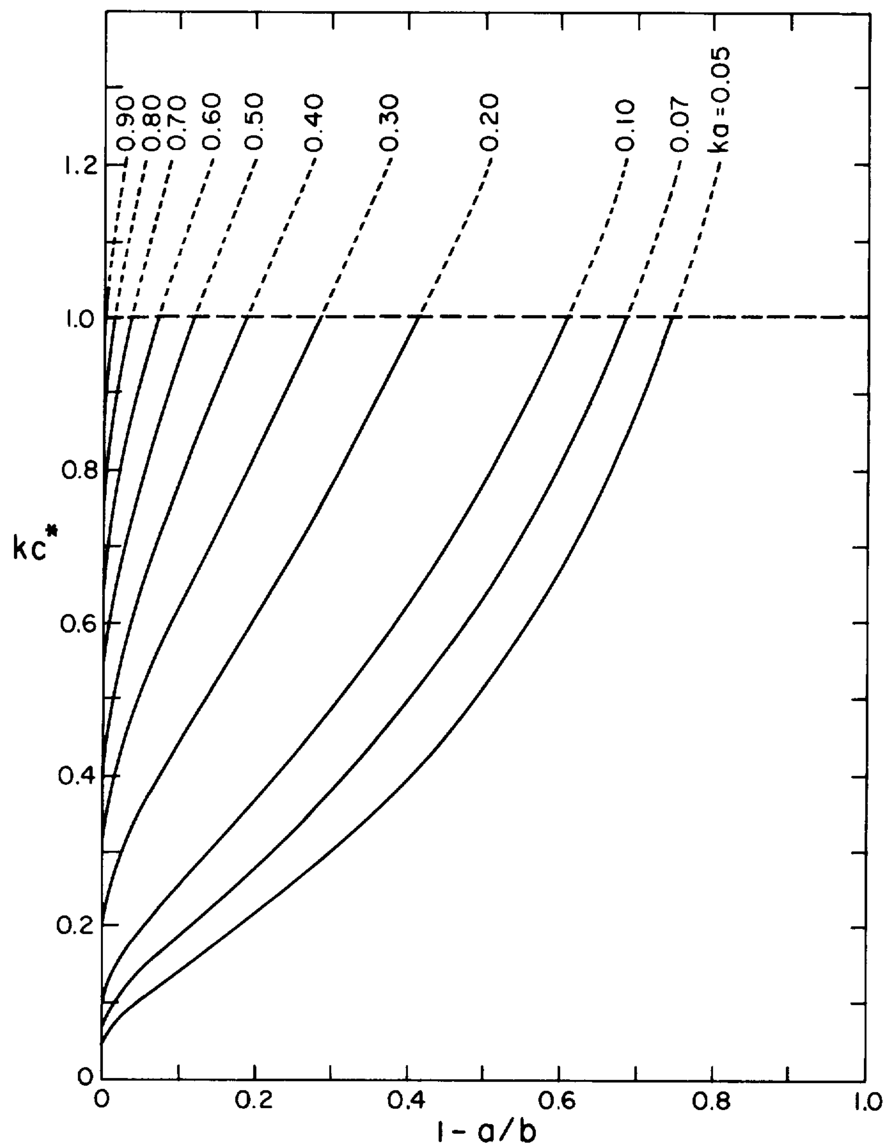

Fig. 8. Stability results for the Plasma Radiation Shield case ($d = \infty$). Regions of stability are above and to the left of each curve of constant ka and regions of instability are below and to the right of each curve. k has the interpretation $1/R$ where R is the major radius of the Plasma Radiation Shield. Thus ka is the radius ratio of the device. Provided the inner edge of the beam is near enough to the spaceship (a sufficiently close to b), the requirements on beam thickness for stability are not particularly stringent. The dashed line at $kc^* = 1$ signifies a geometric upper limit to the allowable beam thickness in the true toroidal shape.

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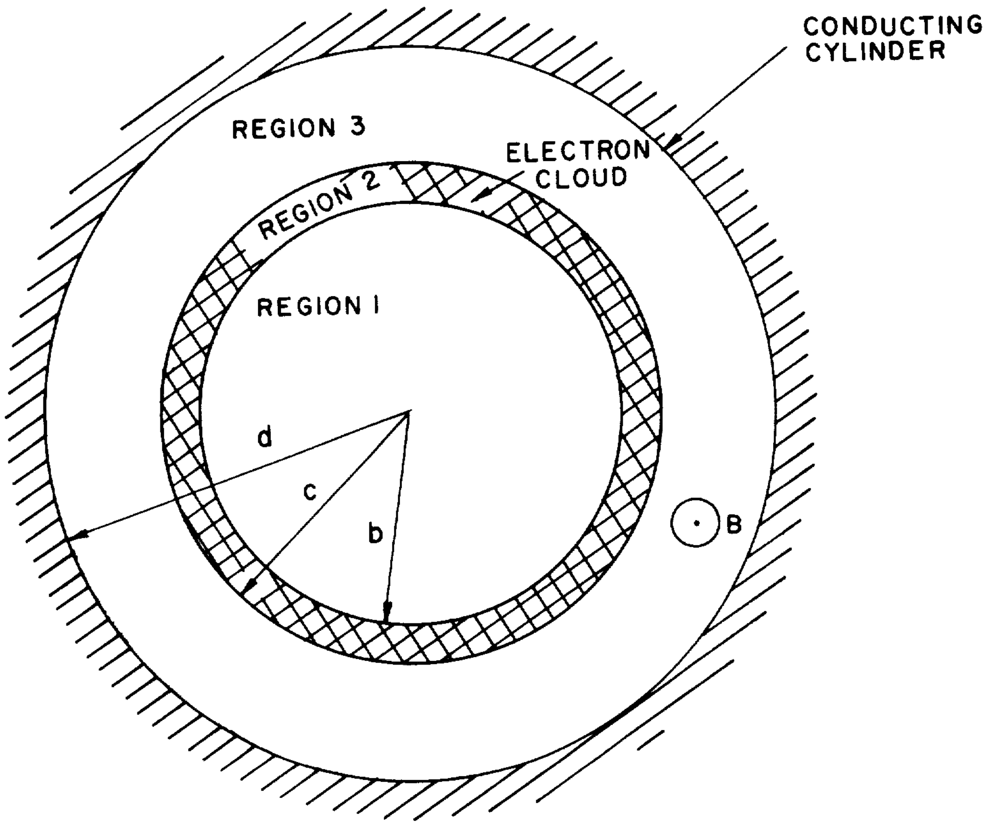

Fig. 9. This configuration differs from that illustrated in Fig. 7 by having the magnetic field axial and the electron motion azimuthal. It therefore refers more to the lab torus (see, for instance, Figs. 21, 22 and 23) than to the Plasma Radiation Shield. Stability calculations for this geometry were done since it corresponds to the laboratory experiment and will provide a test of the theory. Critical stability curves for this calculation are given in Fig. 10.

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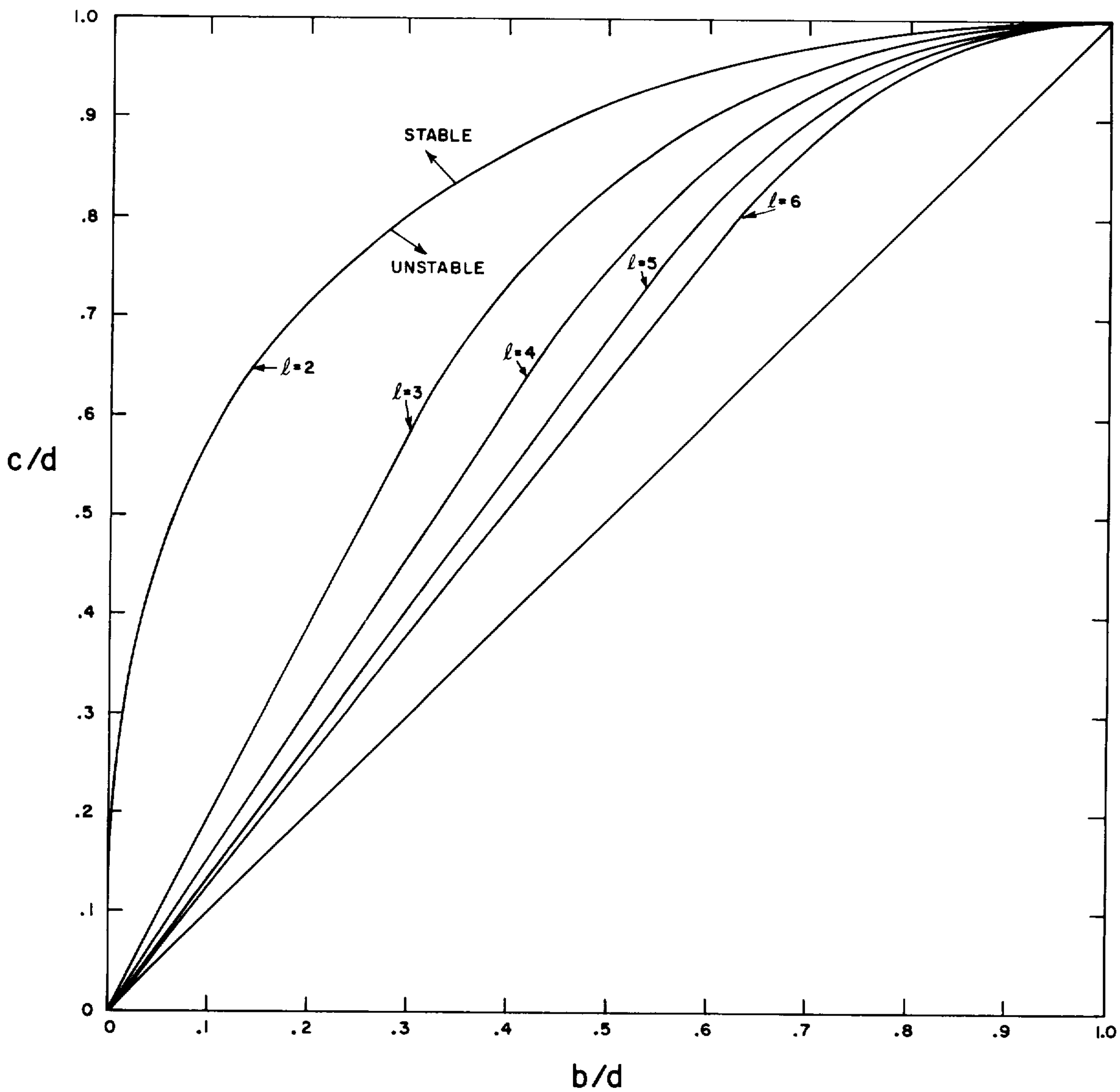

Fig. 10. A stability plot for the geometry of Fig. 9. We deal here in mode numbers rather than wave numbers. The azimuthal modes are denoted by $\ell = 0, 1$, etc. The modes $\ell = 0$ and 1 are always neutrally stable in these cases, and the other modes exhibit stability or instability as shown. The mode $\ell = 2$ is clearly the most dangerous, but this mode (and hence all the others) can be stabilized by having the electron cloud thick enough or near enough to the outer wall.

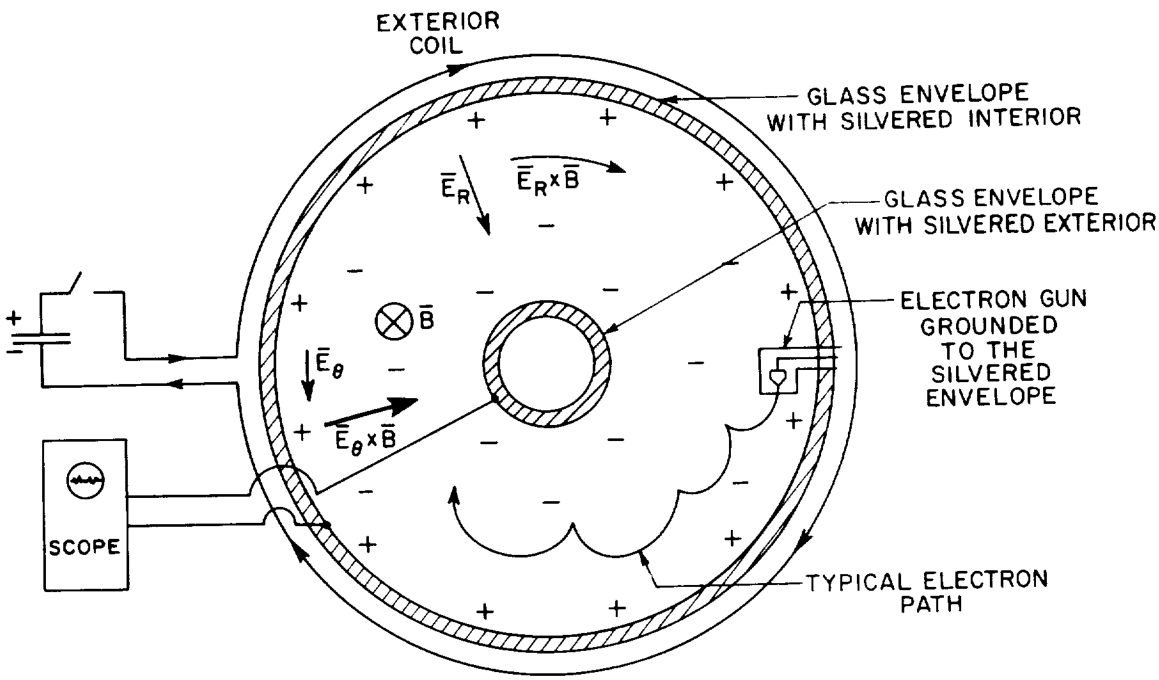

Fig. 11. This figure illustrates an early experimental test of the inductive charging concept. This experiment was straight (rather than toroidal) and had insulators at the ends of the cylinder. There was also an inner concentric cylinder of the same length whose sole purpose was to facilitate the measurement of the electrostatic potential between the axis and the outer cylinder. The outer cylinder was lightly silvered on the inside, and the inner cylinder was lightly silvered on the outside so that the magnetic field could penetrate both surfaces. Electrons were injected by a small gun firing, as shown, in the direction of the E_r/B_z drift. The electrons were then carried inward by the rising magnetic field, those emitted early in the cycle being collected on the inner cylinder. Typical experimental results obtained with this apparatus are shown in Fig. 12.

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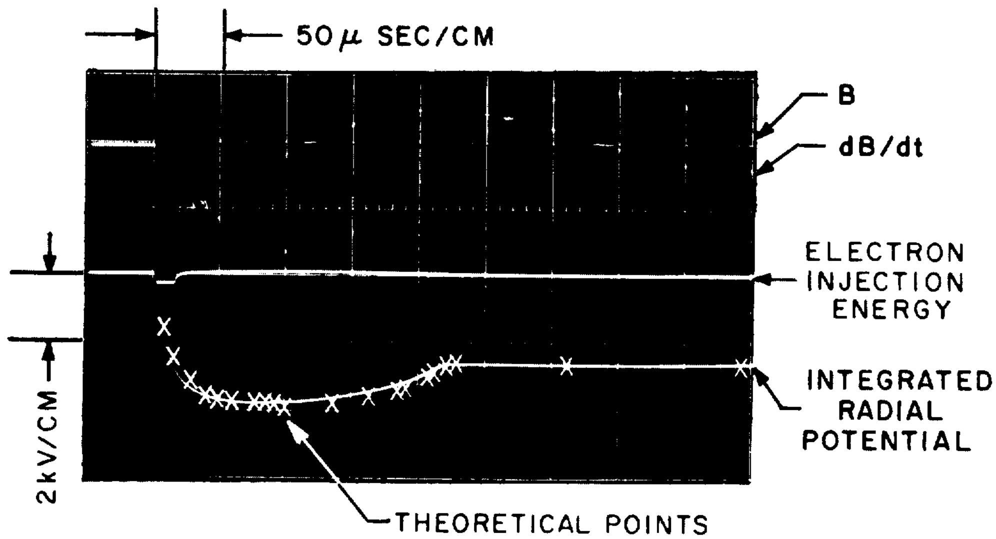

Fig. 12. A typical oscillogram obtained with the apparatus illustrated in Fig. 11. In the upper half, the traces show B and $\dot{B}$; the quarter-cycle time was 100 μ secs. The trace near the axis shows the voltage applied to the electron gun; this was about 200 V for 15 μ secs. The lowest trace shows the variation of the potential between the inner and outer cylinders. A maximum of 4kV was achieved, representing a voltage multiplication ratio of 20. More importantly, the distribution of electrons at different times was calculated assuming ideal adiabatic motion. At each instant of time, the distribution was integrated to give the radial potential; account was taken of the collection by the inner cylinder of electrons whose field lines were compressed inside it. These calculations are indicated by crosses, and are in excellent agreement with the experimental data. The residual potential at the end of the experiment represents the electrons collected by the inner cylinder.

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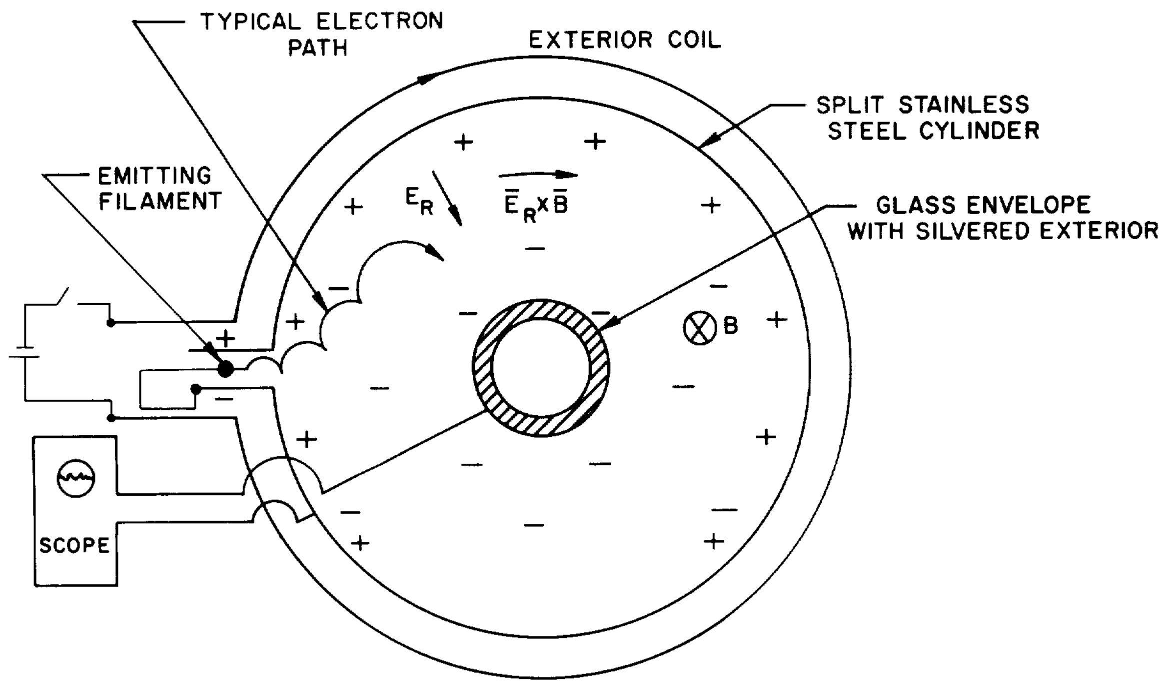

Fig. 13. This experiment is similar to that illustrated in Fig. 11, except that the outer cylinder is now solid metal (i.e. thick compared to the skin depth at the frequency $\dot{B}/B$), and it is slotted. The entire induced electromotive force $\pi a^2 \dot{B}$ now appears across the slot. Hence, all magnetic field lines enter through this slot. The gun now consists of a long heated filament set well back in the slot; no additional electric fields are applied. Results obtained with this apparatus are illustrated in Fig. 14.

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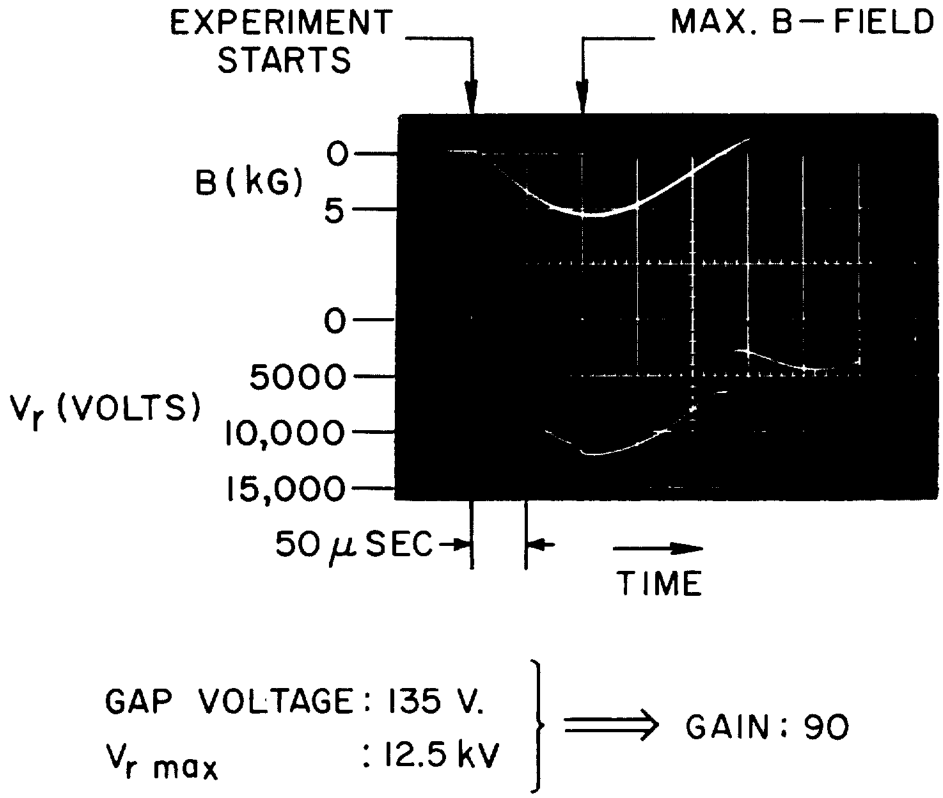

Fig. 14. Results obtained with the apparatus of Fig. 13. The upper trace is $\dot{B}$; it peaks at about 100 μ secs. The lower trace is the potential between the cylinders. The maximum gap voltage (induced by $\dot{B}$) was 135 volts, the peak voltage between the cylinders was 12. 5 kV, yielding a gain of about 90. The traces have no significant interpretation after the magnetic field declines to zero due to the occurence of a discharge on the insulating end plates. A simple estimate of the injection current and hence voltage history that this arrangement should yield has been made. The measured voltage history is in good agreement with this prediction.

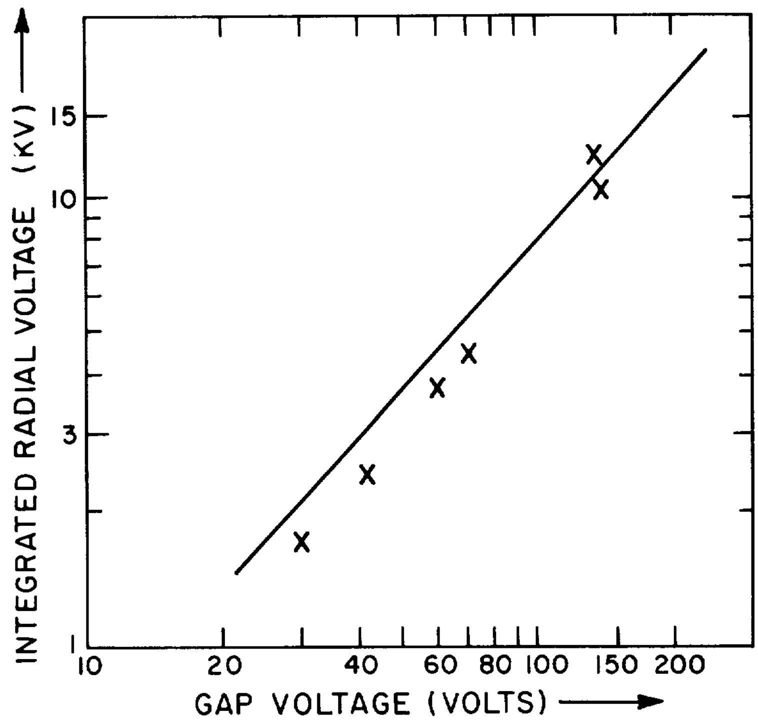

Fig. 15. A plot of results obtained with the apparatus of Figure 13. The maximum integrated radial voltage is plotted against the electromotive force induced in the gap by the magnetic field. The proportionality between these quantities implies a voltage amplification factor dependent basically upon the geometrical configuration only. An indication of our means of calculating this amplification factor is given in Fig. 16. The actual value of the factor in the experiments represented by the points is about 100.

where M , the multiplication ratio (or voltage amplification factor) is independent of B and has a value of about 100 in the experiments giving rise to Fig. 15.

A beginning has been made on the theoretical explanation of this very interesting data. A simple theory yields the injection current vs. time plot of Fig. 16, and this plot seems also to accord with the experimental observations. The theory which lies behind the lines on Fig. 16 yields also a definite prediction for the voltage amplification factor M , to wit:

$$M = \text{const.} \ \frac{R^2}{h^2}$$

where the constant is of the order unity and R and h are respectively the radius of the system and the width of the gap. When modified to allow for the presence of the inner cylinder and some other effects, the numerical value of M calculated according to this theory works out very close to the observed value of 100.

We draw the following conclusions from this state of affairs:

1) Leaving the injection arrangements as they are, but increasing the power in the experiment to make $\dot{\Phi}$ = 10 k V (not an unreasonable value) theory indicates that we should achieve a radial potential of 1 million volts. In fact, this voltage would certainly produce a breakdown of our apparatus, which is linear and has insulating end plates.

2) Increasing the radius ratio (R/h) of the device by 10 (this would be more easily done by making the apparatus larger than by making the gap smaller) should increase the voltage amplification factor from $M = 10^2$ to $M = 10^4$. Thus, a $\dot{\Phi}$ of only 100 volts should yield V_R of 1 million volts, while $\dot{\Phi}$ of 10 k V would yield V of 10^8 volts.

Because of the end problem, neither of these extensions would seem particularly useful in apparatus of the type used so far, but these calculations serve the useful purpose of emphasizing that this means of injection (the modified Kino gun) is sufficiently powerful even in its present elementary state to offer all the injection current that would be needed in a full scale Plasma Radiation Shield.

3. Calculations on the weights of Plasma Radiation Shielding systems are shown in Figs. 17, 18 and 19. These calculations were first presented in the June Quarterly Report, and it has not seemed useful to continue work in this direction for the time being.

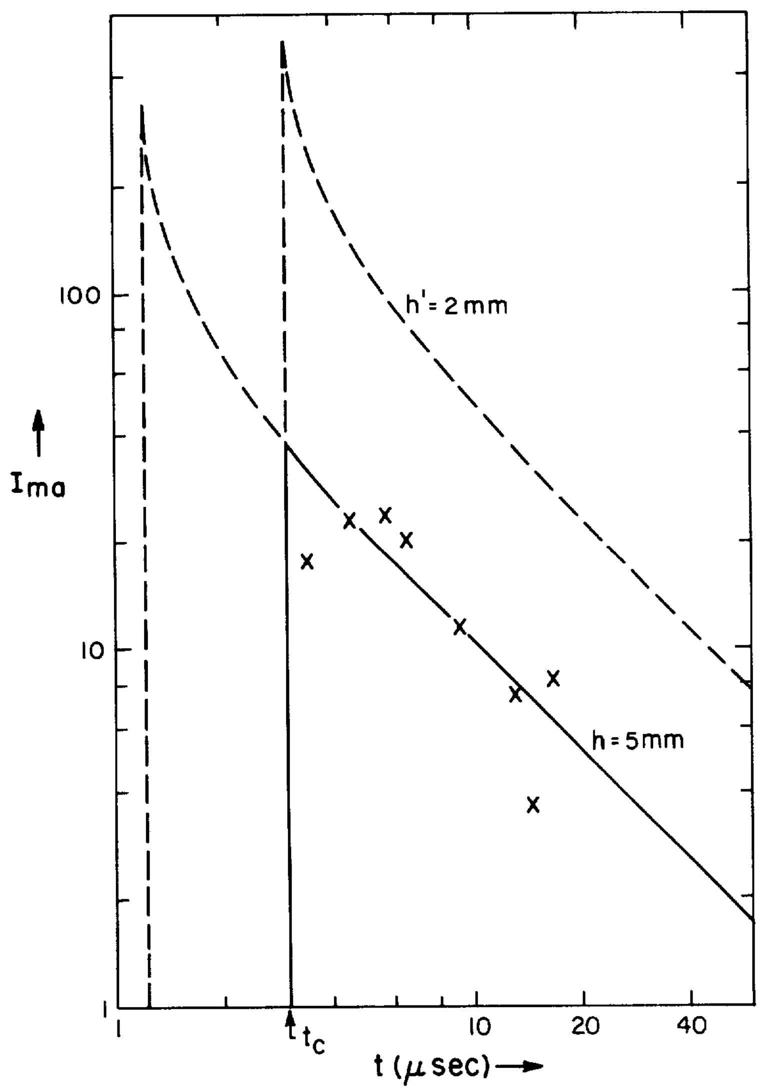

Fig. 16. A theory for the injection current that should be provided by the gun illustrated in Fig. 13 has been developed. The theory predicts no current until the time t_c at which the magnetic field is strong enough to stop electrons from following straight across the gap and subsequently, a declining current as the magnetic field increases to higher values. The theory can be seen to agree reasonably well with experiment. A knowledge of the value of injection current with time and an assumption of subsequent adiabatic electronic motion can be made to yield a value for the voltage amplification factor. This value is in good agreement with the results illustrated in Fig. 15.

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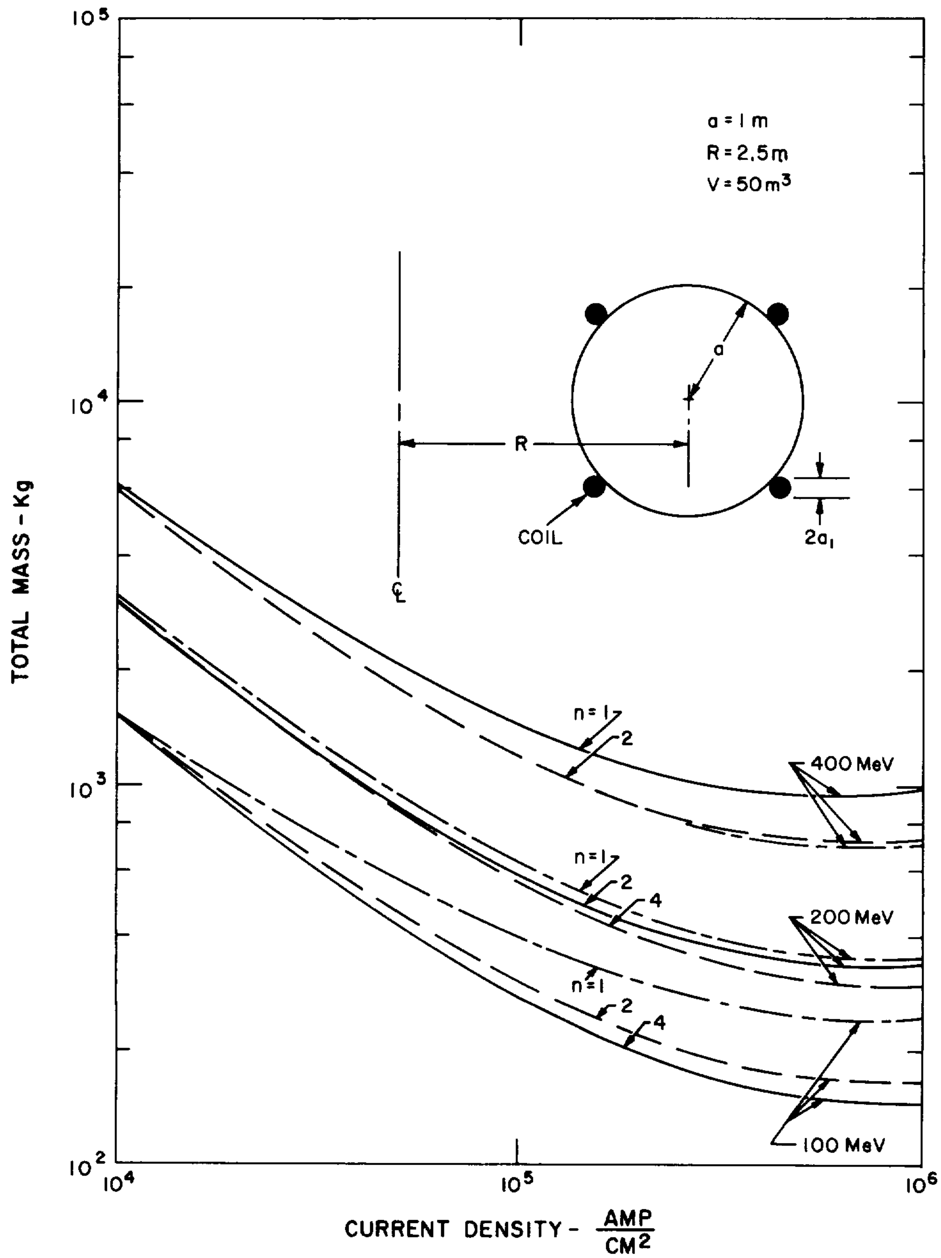

Fig. 17. The estimated weight of a space radiation shield is shown as a function of the current-carrying capacity of the superconductor. Three geometries were treated; the four-coil arrangement shown in the sketch, and a two-coil and one-coil arrangement. A further parameter is the design proton energy.

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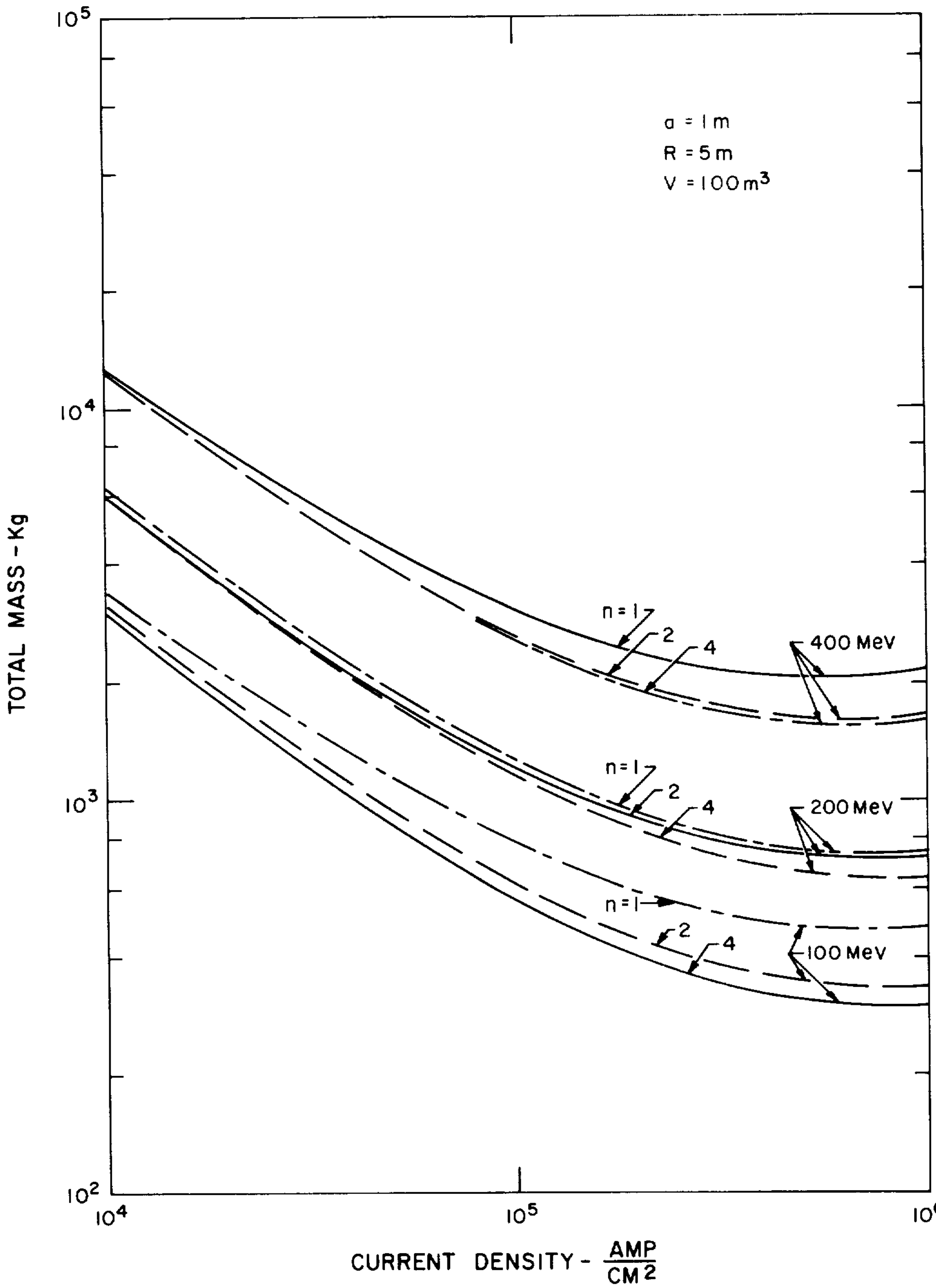

Fig. 18. Like Fig. 17, but for a larger size.

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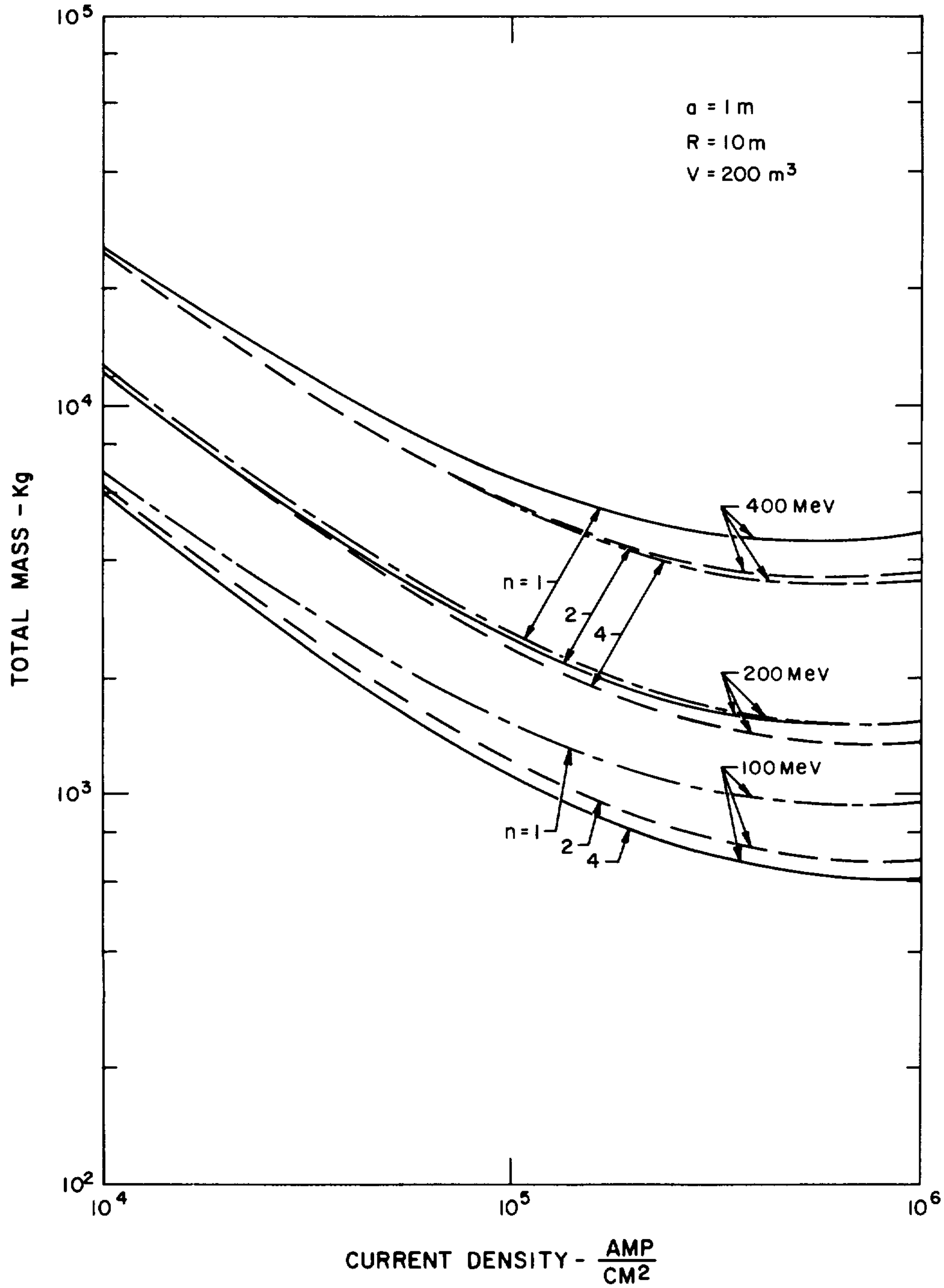

Fig. 19. Like Figs. 17 and 18, but for a larger size.

A4014

III. WORK IN PROGRESS

At the outset of the Plasma Radiation Shield work it was realized that an experiment might be performed in the geometry of the Plasma Radiation Shield provided the penalty associated with having a strut for support could be accepted. At an early date this penalty seemed acceptable and the apparatus illustrated in Fig. 20 was constructed. Certain technical problems concerning the use of this apparatus arose, however, and while these were being circumvented, the experimental results discussed already began to arrive. The consequence of this was that it began to seem increasingly as though the amount that could be learned from the experiment of Fig. 20 was so small (in view of the inherent limitation of the strut) as not to be worthwhile. We have now decided to shelve the experiment of Fig. 20 indefinitely, and to proceed in two other directions, one of which has already been started and one of which has not.

Of these two directions, the first was suggested by the following considerations: two things seem particularly desirable as regards progress from the experiments already made: these are first to go to a toroidal geometry and second to increase all the physical parameters of our systems, especially the radial voltage. An apparatus has been designed and acquired with these objects in view, and it is illustrated in Figs. 21, 22 and 23. No results are expected from this apparatus until at least March or April 1966; at the present writing, the torus has not yet been evacuated. If things go as planned, and depending to some extent on the power available, it might be possible to achieve over a million volts in this apparatus, for roughly 1 millisecond. It is thought that an apparatus in this shape represents the only way of studying toroidal effects or reaching high voltages in the laboratory and for these reasons it is presently the focus of the Plasma Radiation Shielding effort. To support this effort, various related theoretical analyses are also underway.

The second direction consists in taking a fresh look at the problem of experiments on the Plasma Radiation Shield geometry directly. Such experiments would include "dropped" laboratory experiments, actual space experiments and any other possibilities. At the moment all these experiments appear difficult, and a thorough evaluation seems called for. Work along these lines has not yet commenced.

The linear experiment depicted in Fig. 13 has not been dismantled but is now viewed as a supporting experiment for the torus. It is convenient to have this facility as a kind of test bed for electron gun design, probe studies and so forth, since the apparatus is to some extent easier to work with than the torus.

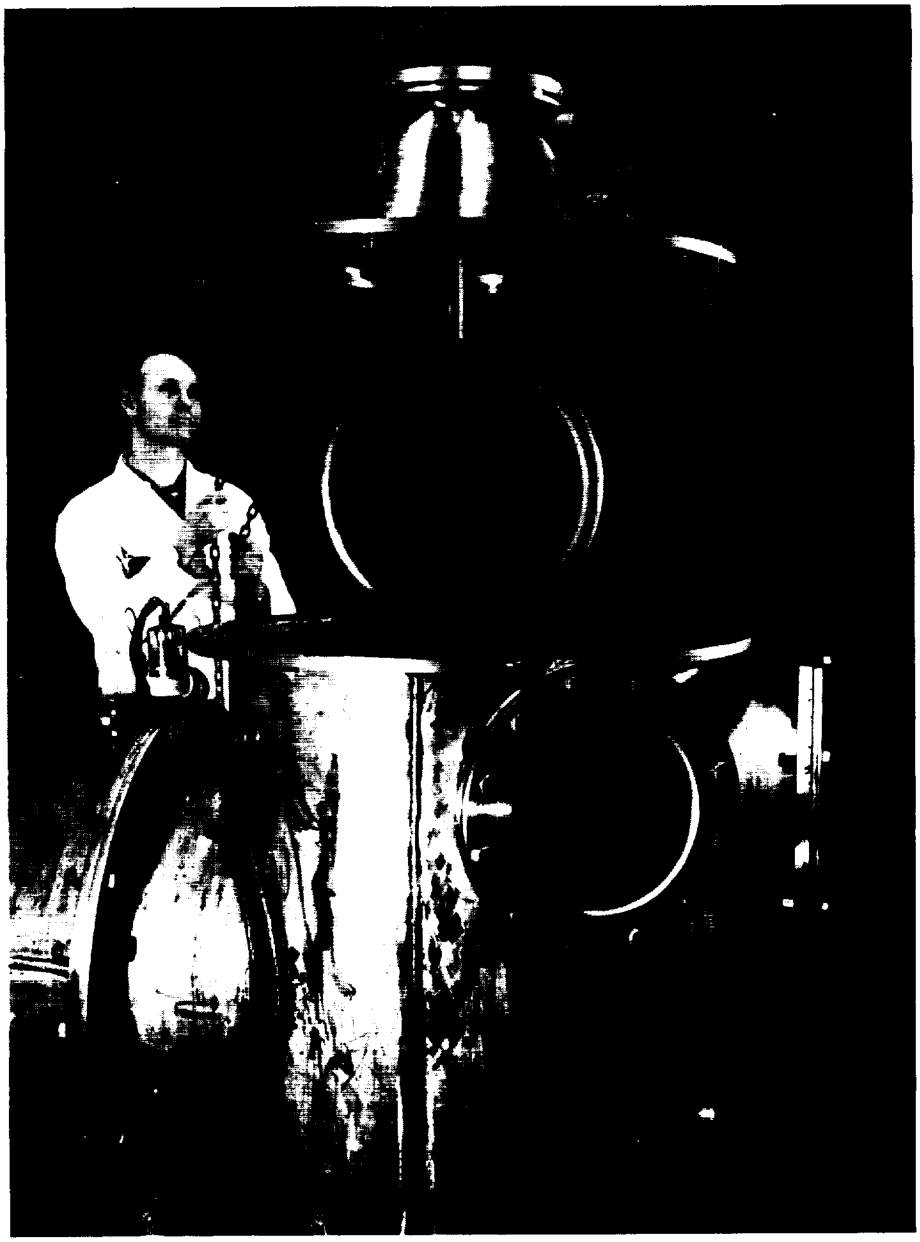

Fig. 20. This experiment was designed to simulate the Plasma Radiation Shield, but the penalties associated with the support strut (an obvious necessity) now make it appear that not much can be learned from this experiment beyond what is already known.

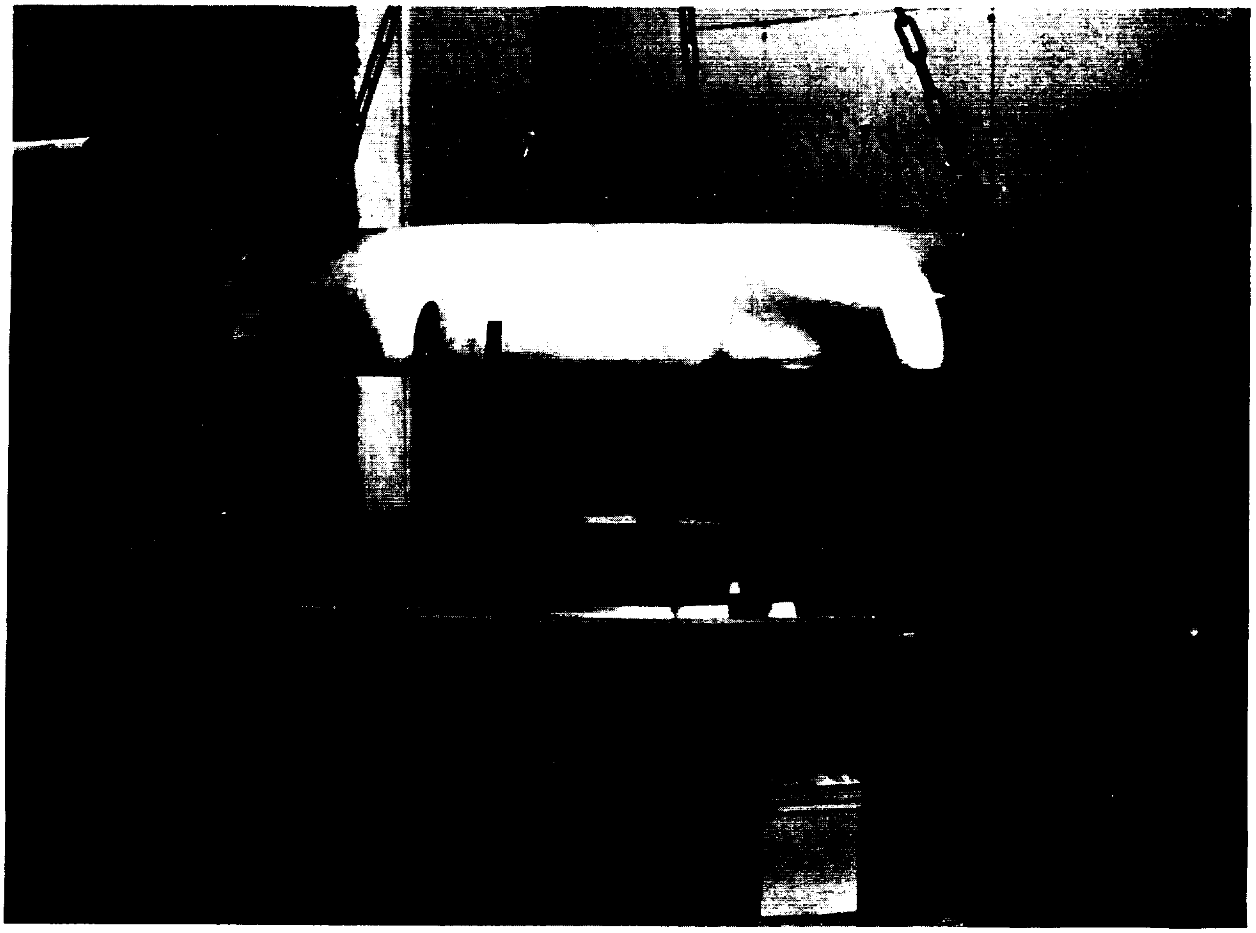

Fig. 21. This experiment, presently being assembled, is designed to study the confinement of electron plasmas in a toroidal geometry even though this geometry is not the one associated with the Plasma Radiation Shield. The minor radius of this torus is about 10 cm. and conditions that might be achievable with it are illustrated in Fig. 24. In particular, it should be possible to establish the basic feasibility of going to very high voltages in devices having only a single electrode apart from the electron cloud. Additional illustrations of this apparatus may be found in Figs. 22 and 23.

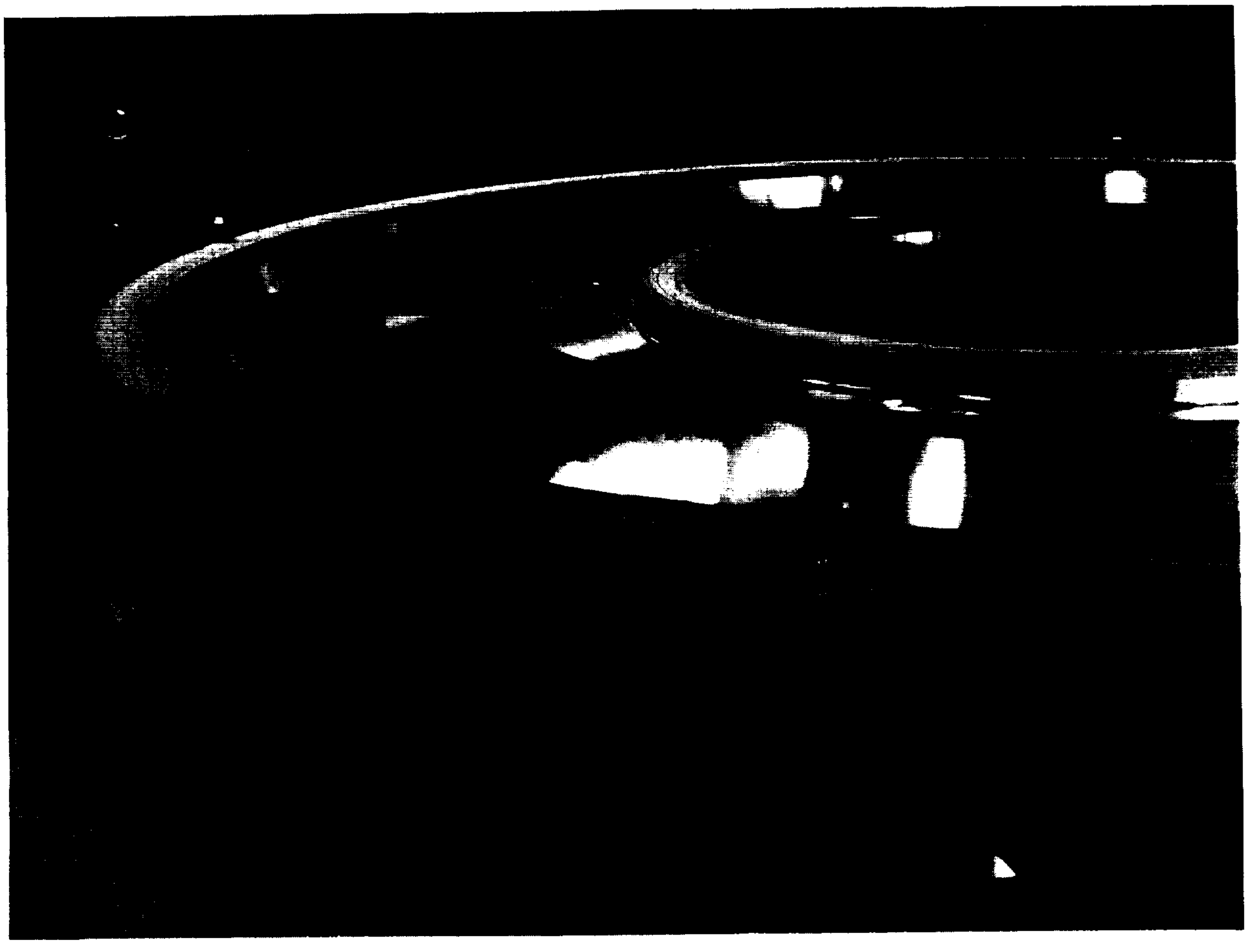

Fig. 22. This illustration shows the region in which the electron gun will be placed. Vacuum seals will be two O-rings and the toroidal interaction space will have a narrow slit at the side facing the major axis. Between this slit and the inner vacuum seal guns of different design may be placed. Vacuum pumping is also performed in this region. One of the pumping ports can be seen in this illustration.

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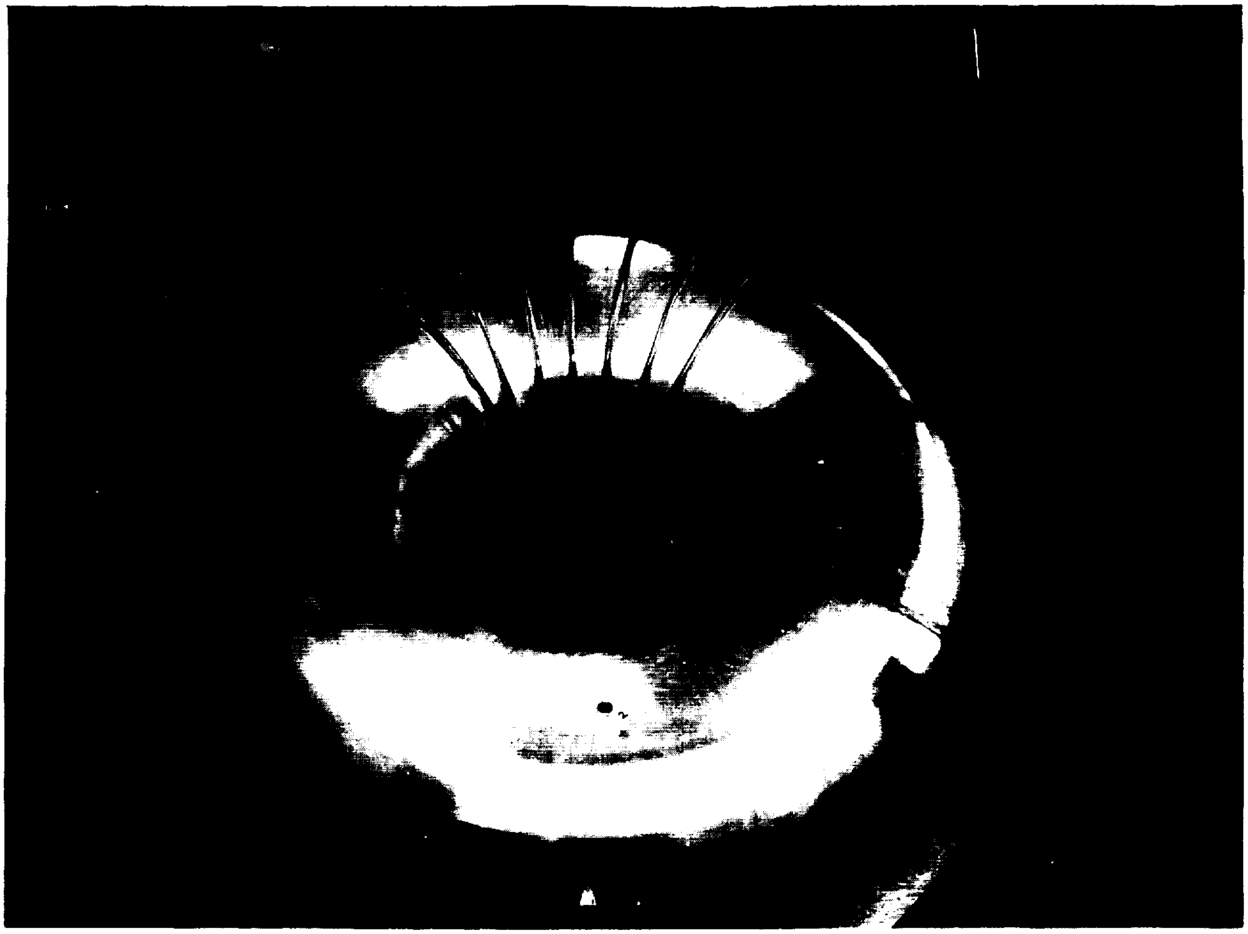

Fig. 23. This illustrates the proposed scheme for winding the field coil around the torus. The magnetic field will be azimuthal and will enter the interaction space through the slot.

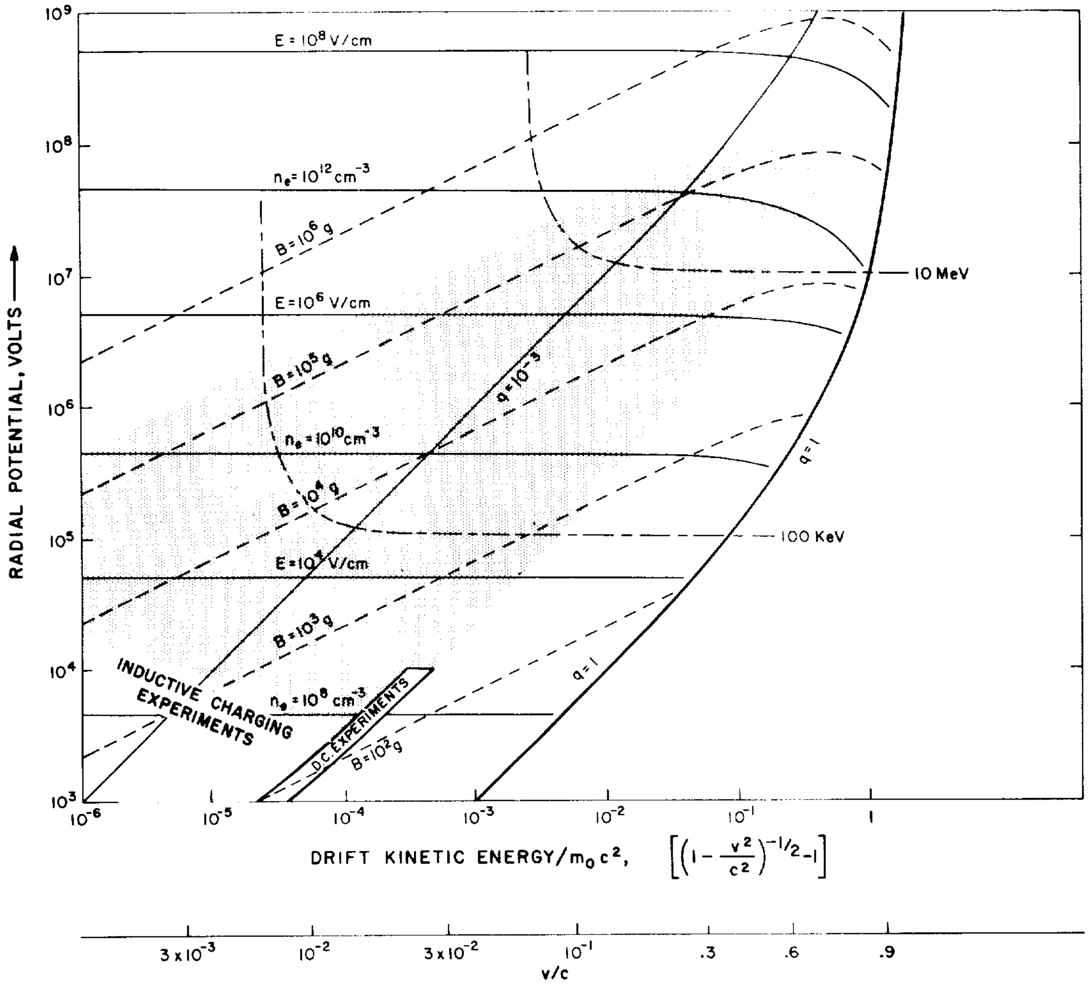

Fig. 24. This "map" shows the various combinations of parameters permissible for the device illustrated in Figs. 21, 22 and 23. The ordinate represents the potential difference between the circular axis and the wall, and the abscissa is $[(1-v^2/c^2)^{-1/2} - 1]$, where $v = E/B$, the drift velocity at the wall. Lines of constant electric field E (wall value), magnetic field B, electron density n_e, and $q = \omega_p^2/\omega_c^2$ are shown. A proton released at the wall will acquire an energy of 100 keV, or 10 MeV along the lines so marked: the bends in these lines occur roughly where the ion Larmor radius is 10 cm, i.e. the dimension of the device. For stronger magnetic fields, the proton energy is limited to the value associated with the E/B drift speed. The hatched area represents an estimate of attainable conditions. It is limited by practically attainable magnetic fields on the order of 100 k gauss, and by the stability boundary at $q \approx .03$. Experiments already performed are shown in the lower lefthand corner but these experiments were performed in linear rather than toroidal geometries.

A3819

IV. ANNOTATED BIBLIOGRAPHY

In this section we review the existing literature on Plasma Radiation Shielding and some related topics pointing out those papers sponsored (or sponsored in part) under the subject contract.

The basic paper on Plasma Radiation Shielding was:

Plasma Radiation Shielding
R. H. Levy and G. S. Janes
Avco-Everett Research Laboratory Research Report 192
American Institute of Aeronautics and
Astronautics Journal 2, 1835 (Oct. 1964)

Abstract

A new scheme is suggested which is intended to make possible the maintenance of a space vehicle at a potential of several hundred million volts above its surroundings. Such a vehicle would be electrostatically shielded against high energy incident protons, but would attract electrons from the interplanetary plasma. The key to the maintenance of the potential is the control of these electrons by a magnetic field. The magnetic field strength required to control these electrons is far less than the strength required (as in a pure magnetic shield) to control energetic protons. As a result, engineering estimates of the weight of this device (assuming superconductors) show that it offers the possibility of a substantially increased shielded volume per unit weight.

Since electrons are to be kept away from the space vehicle by the magnetic field, no useful magnetic field line can intersect the surface of the vehicle. For this reason, the vehicle must be toroidal in shape so that magnetic field lines can link the hole in the center. The magnetic field is provided by a current circulating around the hole in the torus.

The number of electrons which must be tied to magnetic field lines in the vicinity of the vehicle is large enough so that collective motions resembling those found in plasma physics may be present. The outstanding

uncertainty associated with the device is the question of the stability of this electron cloud in the electromagnetic field. No definitive statement can be made on this subject at present.

This paper appeared before the start of the present contract.

The basic paper on the diocotron instability for low values of ω_p^2/ω_c^2 and for periodic geometries was:

The Diocotron Instability in a Cylindrical Geometry
R. H. Levy
Avco-Everett Research Laboratory Research Report 202
Physics of Fluids 8, 1288 (July 1965)

Abstract

The diocotron (or slipping stream) instability of low density ($\omega_p \ll \omega_c$) electron beams in crossed fields is considered for a cylindrical geometry. For a simple density distribution, the normal modes of the electron beam correspond to a continuum of eigenvalues, plus two discrete eigenvalues. Work due to Case and Dikii appears to show that the continuous spectrum is not important in stability studies of this type. The condition for stability considering the discrete modes only is derived; under suitable geometrical and electrical conditions, it is shown that these modes can be stable. The analogy between the electromagnetic problem considered here and the problem of the stability of an ideal rotating fluid is discussed. It is shown that stability conditions derived for the latter problem depend on the possibility of axial perturbations; what this implies for the electron beam problem is briefly discussed.

This paper was sponsored in part under the subject contract.

A paper dealing with the effect of coherent radiation on the stability of a geometry related to that of the Plasma Radiation Shield was:

The Effect of Coherent Radiation on the
Stability of a Crossed-Field Electron Beam
R. H. Levy
Avco-Everett Research Laboratory Research Report 213

Abstract

It has been suggested that a toroidal space vehicle might be raised to a very high positive potential relative to the surrounding space by causing a stable crossed-field

electron beam to circulate around its outer surface. In this arrangement the electric field exists only between the space vehicle and the electron beam; the magnetic field is imposed by coils within the space vehicle. It has been shown that such a beam can be stabilized against the diocotron (slipping stream) instability by being made sufficiently thick. The stability against coherent radiative perturbations of such a thick beam is studied under the following simplifying assumptions: 1) the geometry is taken as infinite cylindrical; 2) the ratio of all frequencies in the problem to the electron cyclotron frequency is negligible; 3) no perturbation electric fields along the magnetic field lines; 4) on the basis of an analogy, but without direct proof, certain continuous spectra of real eigenvalues occurring in the problem are unimportant; 5) the electrons are cold and 6) the outer boundary of the "space vehicle", i.e. the cylinder, is perfectly conducting. It is concluded that if there is a gap between the inner edge of the beam and the cylinder, one unstable mode is present for each azimuthal mode number $\ell \geq 1$.

This paper was wholly sponsored under the subject contract and will appear in the Journal of Applied Physics in December 1965 or January 1966.

A paper prepared for the American Institute of Aeronautics and Astronautics National Meeting (San Francisco, July 1965) was:

The Electron Plasma: Experiment, Theory and Applications

R. H. Levy and G. S. Janes

Avco-Everett Research Laboratory AMP 160
American Institute of Aeronautics
and Astronautics Paper No. 65-538

Abstract

The basic concepts involved in the production and control of pure electron and electron rich plasmas are reviewed, with particular reference to the different geometries in which equilibrium may be achieved. An inductive method of establishing arbitrary equilibrium profiles is described. Recent theoretical work on the stability of some particularly simple equilibria is then discussed. Instabilities considered are: 1) The so-called diocotron (or slipping stream) instability, this instability (whose importance in magnetron work is well understood) is related to the Kelvin-Helmholtz instability in fluid mechanics; 2) A new mode involving spontaneous coherent radiation into space as a result of bunching. This effect can be described as the "flexible

This paper was sponsored in part under the subject contract. It was written with a view to explaining the Plasma Radiation Shield to a generally non-technical audience, although existing experimental and theoretical results are mentioned.

The last paper on electron plasmas was:

On a New Type of Accelerator for Heavy Ions
G. S. Janes, R. H. Levy, H. A. Bethe and B. T. Feld
Avco-Everett Research Laboratory Research Report 235

Abstract

A new device (called HIPAC - Heavy Ion Plasma Accelerator) which may be capable of accelerating ions of any atomic number to energies sufficient to overcome the nuclear Coulomb barrier is described. A closed potential well is created by filling a toroidal vacuum chamber with electrons; the electrons are contained by a magnetic field whose intensity is so low that its effect on the ions can be neglected. Ions are both accelerated and trapped in the well; the trapping effect allows sufficient time for the ions to become highly stripped by electron impact. The very large ion energies that can be achieved in this way would allow a wide variety of nuclear reactions to be studied, including inverse fission. The present primitive state of development of the HIPAC is described, and the future prospects assessed.

This paper deals with an interesting new device based on the geometry of Figs. 21-23. It has been submitted for publication to the Physical Review.

A paper on the diocotron instability for arbitrary values of $q = \omega_p^2/\omega_c^2$ has been in preparation for some time (in collaboration with O. Buneman and L. Linson). Although at this writing it is not yet complete, the results obtained have already been utilized and are illustrated in Figs. 4 and 5. When completed, the paper (which will be sponsored in part under the subject contract, or its successor) will be submitted to the Journal of Applied Physics. The title and abstract follow:

electron beam to circulate around its outer surface. In this arrangement the electric field exists only between the space vehicle and the electron beam; the magnetic field is imposed by coils within the space vehicle. It has been shown that such a beam can be stabilized against the diocotron (slipping stream) instability by being made sufficiently thick. The stability against coherent radiative perturbations of such a thick beam is studied under the following simplifying assumptions: 1) the geometry is taken as infinite cylindrical; 2) the ratio of all frequencies in the problem to the electron cyclotron frequency is negligible; 3) no perturbation electric fields along the magnetic field lines; 4) on the basis of an analogy, but without direct proof, certain continuous spectra of real eigenvalues occurring in the problem are unimportant; 5) the electrons are cold and 6) the outer boundary of the "space vehicle", i.e. the cylinder, is perfectly conducting. It is concluded that if there is a gap between the inner edge of the beam and the cylinder, one unstable mode is present for each azimuthal mode number $\ell \geq 1$.

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The basic concepts involved in the production and control of pure electron and electron rich plasmas are reviewed, with particular reference to the different geometries in which equilibrium may be achieved. An inductive method of establishing arbitrary equilibrium profiles is described. Recent theoretical work on the stability of some particularly simple equilibria is then discussed. Instabilities considered are: 1) The so-called diocotron (or slipping stream) instability, this instability (whose importance in magnetron work is well understood) is related to the Kelvin-Helmholtz instability in fluid mechanics; 2) A new mode involving spontaneous coherent radiation into space as a result of bunching. This effect can be described as the "flexible

antenna instability". Both these instabilities are considered for low density electron beams (that is, $\omega_p \ll \omega_c$). Two experiments are discussed. The object of the first is to produce a stable electron plasma in a simple geometry. The second is designed to test the practicability of the inductive charging scheme. A brief review of selected applications of the electron plasma is also given; these include space radiation shielding and certain high voltage laboratory devices.

In this paper the experimental results of Figs. 11 and 12 were given, as well as a "map" similar to Fig. 24, but for a larger size. It was sponsored in part under the subject contract.

Two short papers published in the Physical Review Letters were:

The Production of BeV Potential Wells
G. S. Janes, R. H. Levy and H. E. Petschek
Avco-Everett Research Laboratory AMP 166
Physical Review Letters 15, 138 (26 July 1965)

Experiments on Magnetically Produced
and Confined Electron Clouds
G. S. Janes
Avco-Everett Research Laboratory AMP 165
Physical Review Letters 15, 135 (26 July 1965)

Of these papers, the first is of a speculative nature, and was sponsored in part under the subject contract. At the time of writing these papers, the idea that a laboratory analogue of the Plasma Radiation Shield could be constructed in the form illustrated in Figs. 21-23 had just occurred. It then appeared that this analogue device might very well have applications in physics quite independent of the Plasma Radiation Shield, such as, for instance, the attainment of extremely high voltages. It was for this reason that the Physical Review Letters was chosen as the appropriate vehicle for publication. The second paper lists the experimental evidence that appeared to support the possibility of actually making the device described in the first paper.

A paper was written adapting the diocotron calculation of Research Report 202 to a geometry more representative of the Plasma Radiation Shield. This was:

The Diocotron Instability in a
Quasi-Toroidal Geometry
R. H. Levy and J. D. Callen
Avco-Everett Research Laboratory Research Report 228

Abstract

The diocotron (or slipping stream) instability of low density ($\omega_p \ll \omega_c$) electron beams in crossed electric and magnetic fields is considered for a cylindrical geometry with a radial electric field and an azimuthal magnetic field. In the analysis the electrons are assumed to have no thermal energy, collisional effects are neglected, the quasi-static approximation is made, and perturbations of the electric field along the magnetic field are ignored. For a simple density distribution the important normal modes of the electron beam correspond to two discrete eigenvalues. A condition for the stability of these modes is derived. This condition shows that, within the approximations of the analysis, the electron beam can be stabilized against diocotron modes of all wavelengths by proper selection of dimensions. The application of this theory to a proposed toroidally-shaped space radiation shield is discussed. Assuming the long straight cylinder geometry to be a reasonable approximation to a torus with a large radius ratio, it is shown that the crossed field electron beam surrounding a space radiation shield will, within the same approximations, be stable against diocotron instabilities when the beam is sufficiently thick.

This paper will appear in the Physics of Fluids for December 1965 or January 1966 and, in view of the subject matter, was fully sponsored under the subject contract.

A review paper on the Plasma Radiation Shield was prepared for publication in Space/Aeronautics. This was:

Plasma Radiation Shielding
R. H. Levy and G. S. Janes
Avco-Everett Research Laboratory AMP 179

Abstract

The principles of operation of the Plasma Radiation Shield are explained and the current status of research on this project is described. The relationship between this device and others using crossed-field electron beams (such as the microwave magnetron) is indicated.

This paper was sponsored in part under the subject contract. It was written with a view to explaining the Plasma Radiation Shield to a generally non-technical audience, although existing experimental and theoretical results are mentioned.

The last paper on electron plasmas was:

On a New Type of Accelerator for Heavy Ions
G. S. Janes, R. H. Levy, H. A. Bethe and B. T. Feld
Avco-Everett Research Laboratory Research Report 235

Abstract

A new device (called HIPAC - Heavy Ion Plasma Accelerator) which may be capable of accelerating ions of any atomic number to energies sufficient to overcome the nuclear Coulomb barrier is described. A closed potential well is created by filling a toroidal vacuum chamber with electrons; the electrons are contained by a magnetic field whose intensity is so low that its effect on the ions can be neglected. Ions are both accelerated and trapped in the well; the trapping effect allows sufficient time for the ions to become highly stripped by electron impact. The very large ion energies that can be achieved in this way would allow a wide variety of nuclear reactions to be studied, including inverse fission. The present primitive state of development of the HIPAC is described, and the future prospects assessed.

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A paper on the diocotron instability for arbitrary values of $q = \omega_p^2/\omega_c^2$ has been in preparation for some time (in collaboration with O. Buneman and L. Linson). Although at this writing it is not yet complete, the results obtained have already been utilized and are illustrated in Figs. 4 and 5. When completed, the paper (which will be sponsored in part under the subject contract, or its successor) will be submitted to the Journal of Applied Physics. The title and abstract follow:

The Stability of Crossed-Field Electron Beams

Abstract

The stability of crossed-field electron beams is treated for arbitrary values of the parameter $q = \omega_p^2/\omega_c^2$ = (plasma frequency/cyclotron frequency)^2. The theory bridges a gap between existing theories applicable for $q \ll 1$ and for $q = 1$. For wavelengths longer than several beam thicknesses, an instability occurs which is not importantly affected by the value of q. For short wavelengths a cyclotron instability occurs with a growth rate declining roughly as exp $(-2/q)$. It generally becomes unimportant for $q \lesssim 0.1$. These results are useful in explaining a number of experimental observations.