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such as deflection plates. Figures 152—157 show the deflection near the edges of the chamber; as expected, it is elliptical, and the orientation of the ellipses is the orientation to be expected from the induced electric field of the three rf coils when they are symmetrically placed and operating with conventional three-phase currents. That is, the major axis of the ellipse should be parallel to the flatter side of the nearest coil. Reference to the location of coils, Figure 23, will verify this. (Coil one is at 18 degrees counter-clockwise from 12 o'clock.)

The CR tube had the usual aquadag wall coating, and for this reason the electric field of the rf electrodes would not penetrate the CR tube. No deflection was produced with any amount of applied rf electric field; therefore, there are no pictures of beam deflection by electrode voltage. This observation points out the difference in shielding ability of a semiconductor layer against magnetic rf fields and against electric fields. The magnetic rf field penetrated well, and only a few hundred volts across the coils caused enough current flow to deflect the beam as shown in these pictures. One may say, therefore, that the magnetic rf field and its associated induced electric field should have better penetration into a plasma than will the electric rf field of the electrodes.

Although the spot in the 1EP1 CR tube focussed nicely, the beam in the remounted assembly (Figure 35) would focus only as a line 1/4 to 3/8 of an inch long. It was found that stray 60-cycle magnetic
fields were the cause of the line. However, the beam apparatus was used to obtain several informative pictures before correction for this stray field was made.

In Figure 158 and following, showing electron beam traces, using the remounted gun assembly, the phasing and voltages refer to oscilloscope measurements of phase and voltage across the rf load coils and on the electrodes. Coil 1 voltage was used as phase reference. A trigger signal from the 1.86 megacycle crystal oscillator supplied an independent phase reference for the Tektronix 517A oscilloscope sweep.

The large patches of light surrounding the central dark area (the screen) are caused by light that came around the square sides of the screen from the electron gun filament and was reflected in the three-inch Pyrex pipe. The electron beam trace in Figure 159, for example, is the oval-shaped ring about $5/16$-inch in diameter.

In Figures 158—161 of December 10, 1961, the phasing was the same as that for all former plasma observations such as those represented by Figures 36—146, producing the electric and induced electric fields theoretically in phase. These pictures indicated that there was some addition of fields, but not complete algebraic addition; the indication, therefore, was that the electric and induced electric fields were not in phase.

On December 11, 1961, the phases were changed as given in Figures 162—165, so that the rotating electric and induced electric fields with which we are concerned should theoretically have been out of phase. (Phase changes of 120-degree or 180-degree combinations are possible by rearranging cables to grids of 813's and 833A's.) The
fields were not out of phase, but there was addition such that the resultant deflection, Figure 165, is greater than either of the individual deflections, Figures 163, 164.

This curious behavior led to some doubt whether there were true rotating fields at the fundamental rf frequency within the rf assembly; a test for counter-rotating force fields was therefore made, as represented by Figures 166—174, showing the (expected) traces for vectors rotating in opposite directions at the same frequency. Since there is no physical basis for the electric field (of the electrodes) to be rotating at any but the fundamental frequency, one may infer that both the induced electric and the electric fields rotate at that frequency. Furthermore, from these pictures and preceding Figures 158—165, the individual rotating vectors are of essentially constant magnitude. Changing the magnitude of excitation of one set of elements, either electrodes or coils resulted in behavior illustrated by Figures 169 and 170.

Either mechanical or electrical phase change of the electrode voltage with respect to coil voltage results in a change of linear deflection angle, with respect to the vertical (Figure 171).

All manipulation of angular position of the electrode ring, and of the excitation amplitude verified that the force fields are each of the nature expected; that is, they are each vector fields of nearly constant magnitude rotating at nearly constant rate and at the fundamental excitation frequency.
Figures 166—170. Description:

Figure 166, 3 - $\mathcal{O}$ electrodes and 3 - $\mathcal{O}$ coils excited.
Figure 167, 3 - $\mathcal{O}$ coils only excited.
Figure 168, 3 - $\mathcal{O}$ electrodes only excited.

Phase adjustments:

Coil 1, $0^\circ$  
Electrode 1, $0^\circ$
Coil 2, $120^\circ$  
Electrode 2, $240^\circ$
Coil 3, $240^\circ$  
Electrode 3, $120^\circ$

Mechanical, original geometry as per Figure 23

In Figures 166—168, voltages were balanced to produce the line of Figure 166. In Figure 169 both 3 - $\mathcal{O}$ electrodes and 3 - $\mathcal{O}$ coils are excited, but electrode voltage has been increased. Figure 170 shows deflection produced by this increased electrode voltage.

Figures 171—174. Description:

Figure 171, 3 - $\mathcal{O}$ electrodes and 3 - $\mathcal{O}$ coils excited, counter-rotations.
Figure 172, 3 - $\mathcal{O}$ coils only excited.
Figure 173, 3 - $\mathcal{O}$ electrodes only excited.
Figure 174, 3 - $\mathcal{O}$ electrodes and 3 - 0 coils excited, rotations both in same sense.

Phase and voltage adjustments, Figures 171—173:

Coil 1, $0^\circ$, 400 v peak rf.  
Electrode 1, $56^\circ$, 350 v peak rf.
Coil 2, $120^\circ$, 400 v peak rf.  
Electrode 2, $296^\circ$, 350 v peak rf.
Coil 3, $240^\circ$, 400 v peak rf.  
Electrode 3, $176^\circ$, 350 v peak rf.

(In Figure 174, phase on electrodes 2 and 3 were revised so that electrode 2 was at $176^\circ$ and electrode 3 at $296^\circ$.)

Mechanical, electrode 1 was $90^\circ$ ccw from coil 1 viewed from south end.

The observed fact that amplitude of deflection does not change appreciably when the spot is decentered showed that the fields have nearly the same amplitude at the center as elsewhere; variation in amplitude with radius is small.

At this time the electron gun broke down electrically between the lens elements. It was replaced by a new gun which was taken from a 5BP1 CR tube while in a helium atmosphere, and was installed in the vacuum chamber also in helium. This gun gave almost normal emission, and it has never been operated at over 2000 volts so that it has never broken down.

On December 21, 1961, the new gun, with a new phosphor screen cut from a CR tube face was installed and was employed in recording all succeeding electron beam pictures. (A 60-cycle inductor was installed at about one foot from the gun, to cancel the interfering 60-cycle field. The phase of current in the inductor happened to be correct to allow cancellation after some effort to find the correct orientation of the inductor.)

In Figures 175—178, the electrodes were shifted 76 degrees electrically from the phasing that theoretically would produce cancellation of the rf fields. Under this new phase adjustment there was more cancellation than previously encountered, but still not perfect cancellation. A mechanical shift in phase by the same amount was suggested by this observation.

Figures 179—182 show the results of adjustment of electrical phases without maintaining the usual 120-degree relationship between

Figures 179-182. Electron Beam Traces, Same Conditions as in the Above Figures, Excepting New Electrical and Mechanical Phasing of the Electrodes Was Introduced.

electrodes. After a mechanical shift, the phases of electrodes were changed (electrically) individually while watching the deflection, and an approximate balance of electrode and coil fields was obtained. In the next Figures 183—186, direction of rotation of the electric field was reversed by reversing two electrode amplifier leads, and the approximately linear deflection of Figure 183 resulted.

Amplitudes of electrode and coil excitations were then increased, an amplitude balance was obtained by varying 513 plate voltage without changing any other tuning adjustments, (Figure 184), and the components were observed as in Figures 185 and 186.

It was thus shown that it should be possible to attain nearly perfect balance between the field of the electrodes and of the induced electric field of the three-phase coils, and still maintain nearly full rf output power of the 813 and 833-A amplifiers. (In the phase adjustments to this time, in order to achieve cancellation, the amplifiers had to be detuned so that they were operating somewhat inefficiently.) Repositioning the electrode ring and readjustment of the phases did permit efficient operation of the amplifiers, so that a balance between the two fields was obtained with permissible increase of rf power to full rated output capability of the class C amplifiers. See Figures 187—194. It should be noted that there is some phase change with power output, necessitating a readjustment of the tuning when power output is varied greatly. This can readily be done by tuning while observing the required phases on the oscilloscope.
INTRODUCTION

Because of the large amounts of energy released in nuclear reactions involving deuterium and tritium\(^1\), such as

\[
\begin{align*}
1D^2 + 1D^2 &\rightarrow 2He^3 + 0n^1 + 3.27 \text{ mev}, \\
1D^2 + 1D^2 &\rightarrow 1T^3 + 1H^1 + 4.03 \text{ mev}, \\
1D^2 + 1T^3 &\rightarrow 2He^4 + 0n^1 + 17.6 \text{ mev},
\end{align*}
\]

because of \(1D^2 + 1T^3\) regarding availability of these fuels, it has become desirable to produce these reactions at high density in the laboratory. A successful production of such "fusion" reactions at a high reacting particle density in the laboratory would be the first step toward a commercially attractive energy source for electrical power production in great industrial quantity.

All work toward the realization of such a "fusion reactor" has shown that the reacting elements must be contained by magnetic forces, and that electrostatic forces are not practical for containment. The latter fact is attributed to the necessary presence of electrons as well as positive ions in any practical plasma of the reacting elements; thus, excessive amounts of electrical current result when any appreciable electrical field exists in or at the edge of the plasma. ("Plasma" throughout this paper will mean a gas sufficiently ionized to have a conductivity very much greater than its non-ionized conductivity.) In the experiments to be described neutral gas was contained in a Pyrex glass chamber, and a mirror magnetic field was used as the container of charged particles.
Figures 187—190. Phase and voltage adjustments:

Coil 1, 0°, 1200 v peak rf  Electrode 1, 0°, 900 v peak rf
Coil 2, 120°, 1150 v peak rf  Electrode 2, 115°, 960 v peak rf
Coil 3, 240°, 1150 v peak rf  Electrode 3, 202°, 800 v peak rf

Mechanical, electrode 192° counterclockwise from coil 1, viewed from geographic south end of dc magnet.

Figures 191—194. Phase and voltage adjustments:

Coil 1, 0°, 1200 v peak rf  Electrode 1, -7°, 760 v peak rf
Coil 2, 120°, 1200 v peak rf  Electrode 2, 113°, 760 v peak rf
Coil 3, 245°, 1150 v peak rf  Electrode 3, 233°, 760 v peak rf

Mechanical, same as above.

Later Plasma Observations

After the desired balance of rotating fields (induced electric field 180 degrees from electric field) was achieved as indicated in Figure 194, the electron gun was removed from the gas chamber.

A phosphor screen assembly as illustrated in Figure 195 was placed 1-\frac{1}{2} inch from maximum magnetic field. Charged particles leaving the magnetic "bottle" follow spirals along the direction of magnetic field, and excite the phosphor in spots of diameter at least equal to the .055-inch diameter holes in the baffle. Supposedly, enlargement of the spots would indicate an increase in particle energy.

The plasma apparatus was run on January 22, 1962, first with deuterium, then with hydrogen.

There was not any appreciable enlargement of spots on the screen with a change of dc magnetic field or with change of gas pressure. The phosphor screen performed satisfactorily excepting that current impinging on the spots through holes in the baffle was much too great, and these spots in a few minutes became inactive because of phosphor burnout. (If some means can be devised to reduce the current density, this type of screen will be of some diagnostic value.) Before the spots (not shown) became burnt out, they were of very uneven brilliance. Only two on the edge were very bright, one on the edge was less bright, one was faintly visible, and the center was very faint. The three fairly bright spots on the edge are the ones that subsequently burnt. Three polished lines were later found on the metal baffle corresponding to the three bright regions of Figures 196 and 198.
(a) Baffle and Phosphor

(b) Position of Baffle and Phosphor in Gas Chamber

Figure 195. Baffle and Phosphor Device
For all Figures 196—200:

Phases, electrical—

Coil 1, 0°, 1600 v  Electrode 1, -7°, 2100 v
Coil 2, 120°, 1600 v  Electrode 2, 113°, 2100 v
Coil 3, 240°, 1600 v  Electrode 3, 233°, 2100 v

DC magnet current 850 amperes.

(Above voltages are peak rf volts.)
Polaroid type U7 film, 1/10 sec f/8.
Pressure, 6 microns except where noted.

Figures 196—200. Discharges in Deuterium and Hydrogen with Rotating Force Fields 180° Out of Phase; Pressures as Noted.
On the first part of the run with deuterium (Figures 196, 197) it was desired to see if there was any noticeable change in plasma appearance when dc magnet current was varied through the theoretical deuteron cyclotron frequency, corresponding to a magnet current of 860 amperes and 2,410 gauss at 1.86 megacycles. There was no obvious change in the appearance of the plasma over this region of magnet current. Observation was made at 35 and 6 microns. Phases and voltages were as listed for Figures 196—200. This phasing theoretically would cause drifting of cyclotron-accelerated ions toward the center region of the bottle.

Amplitude of rf voltage on the electrodes was then varied; a minimum in light output of the ionized gas was observed at a certain rf electrode voltage. This indicated that the rf fields of coils and electrodes were behaving, even in the presence of the ionized gas (at 35 microns), to some significant extent as they would in a vacuum. However, it was realized, and verified on the oscilloscope, that there was some phase change of electrode voltage as voltage amplitude was varied; for this reason one should not have expected to achieve perfect phase balance, between the rotating fields, at some lower electrode voltage when the correct phasing was set for higher electrode voltage.

When the phasing was as in the original balanced condition as given opposite Figures 191—194, the gas was observed visually while amplitude of rf voltage on the electrodes was varied, with no dc magnetic field. The observable ionization would cease completely when
the electrodes reached the amplitude (760 peak volts) for minimum deflection of the electron beam as previously used. Thus, it was shown that there is enough penetration of the gas even at 35 microns so that some of the desired action of the electrode-coil assembly takes place. A sketch of the visually-observed qualitative behavior of light output of the gas as a function of volts on the electrodes is presented in Figure 201 (under the latter described conditions).

Essentially the same behavior resulted when ordinary hydrogen was run. The pictures, also taken from the end of the gas chamber, are presented in Figures 198—200. It is evident that there is an intense region at the maximum magnetic field vicinity comprising three bright linear areas. As could be visually observed, these bright spots were at the ends of three bands of illumination which ran the complete length of the magnetic bottle following approximately the contour of the dc magnetic lines of force.
Figure 201. Qualitative Sketch of Light Output of Gas as a Function of Electrode Excitation
CHAPTER III

CONCLUSIONS

Summary of Theory

It was mathematically shown that within an equilateral triangle of three-phase currents there is a rotating induced electric field on a charged particle located within the triangle, and that this field rotates in the same sense at all points within the triangle, but not at the same angular speed at every point. The analytical value obtained for the induced electric field at the center was corroborated by a vector geometric addition of induced forces at the center.

Conclusions from Experiment

A three-phase four-kilowatt radio-frequency generator was successfully constructed and operated as a means of ionizing gases within a three-inch diameter Pyrex glass cylinder. Three-phase coils and three-phase electrodes were powered by this generator to produce (1) a rotating induced force field experienced by charged particles within the center region of the coil geometry, (2) a rotating electric field produced by three-phase electrodes. A mechanical or electrical rotation of the electrodes with respect to the coils produces a shift in relative phase of the two associated force fields; there is a phase discrepancy between theory and experiment of about 90 degrees not yet explained.
An electron beam from a CR gun was shown to be adaptable for measuring the relative field strengths in the three-phase rf coil and electrode assembly. It was possible to control the electron beam inside a three-inch diameter glass vacuum chamber over a beam trajectory of 11 inches, with no conductive coating on the glass.

The rotating-field rf coil and electrode assembly, mounted external to the glass and powered by two kilowatts, reliably ionizes hydrogen or deuterium gases at a pressure of 1.6 microns and above, when associated with a mirror magnet of 1000 gauss at center and a mirror (gauss) ratio of 3.5/1, with no other ionizing agent such as internal electrodes or radiations being used. Decreasing magnetic field from near 1000 gauss to zero gauss requires higher pressure for ionization; also, a decrease in rf power supplied to the coils and electrodes requires higher pressure for ionization. (Since at 10^{-4}mm pressure the mean free path of the gas becomes near the greatest dimension of the gas chamber, an avalanche of electrons does not take place; thus, it is expected that great increases in rf power would be required to ionize gases below this pressure in the present apparatus.)

The gas discharge produced by three-phase fields of the coil and electrode assembly differs in some visible respects from a discharge produced by single-phase operation of the same assembly.

There is sufficient field penetration at 35 microns such that a cancellation of the electric field by the induced electric field of the coils can be brought about so as to cause the discharge to cease,
Fusion reactions require several thousand electron volts (ev) of reacting particle energy; therefore, some means of energizing the contained ions is required. In these experiments three-phase radio frequency fields were investigated as a means of producing a plasma and of energizing ions in the mirror magnetic containing field. Steady, unmodulated radio-frequency fields were applied; this is in contrast to pulsed radio-frequency work carried on in many plasma laboratories.

Studies at this institution have shown\(^2\) that rotating electromagnetic fields may be used with a dc magnetic field to energize ions as well as cause them to drift toward the axis of the rotating fields. If such central drifting can be made to occur, an increase in temperature over conventional single-phase excitation should be possible, because contact of ions with the (glass) walls would be reduced.

Broadly stated, the experiments to be described were to determine whether in the mirror field a plasma can be produced using three-phase rf excitation at pressures of the order of 1 micron without electrodes internal to the vacuum chamber, how a plasma behaves in three-phase fields produced by a few kilowatts of radio-frequency power, and whether it would be advisable to conduct three-phase rf experiments with a higher power rf generator. The rf power used here is much less than that at other plasma laboratories, involved in rf heating.

In 1957 a study was under way at this university, sponsored by the Air Force, to survey the thermonuclear problem. Several schemes
and this cancellation occurs with the same adjustment of fields that causes field cancellation in a vacuum.

In searching for a cyclotron-resonance manifestation there has been no clear-cut success as yet. Several reasons have been pointed out as a result of the experimental work. Two of these are: (1) the gases introduced into the gas chamber are of the molecular form; if the cyclotron frequency of the molecule is that of the rf fields, then molecules can be accelerated and dissociated, but no appreciable cyclotron energy can be supplied to the atoms; (2) if the operating rf frequency is the atomic cyclotron frequency, then before an atom can be accelerated by the cyclotron effect it must be dissociated from the molecule; this takes a few electron volts, and if there is not a great enough energy density in the plasma there will be a small percentage of atoms as compared to molecules. Another possible reason for not being able to observe a pronounced cyclotron effect is that pressures used thus far have been too high for proper operation of the resonance device, so that charge exchange neutralizes ions as fast as they can be produced.

It has been experimentally shown that a rotating induced force field acts upon a charged particle in the center region of the three-phase coil assembly, while there is an actual rotating magnetic field. The magnetic field has essentially zero magnitude at all times in the center of the coil assembly, while its rotating induced electric field has a constant non-zero magnitude at the center and a non-constant
magnitude at all other points in the central region of the assembly. Observed rotating fields within the rf assembly agree with theory.

At 1.86 megacycles magnitude of the induced electric fields of the coils can be comparable to the magnitude of the electric field of the electrodes when the rf sources have comparable power capability.
APPENDIX

MEASUREMENT OF MAGNETIC FIELD IN AN ARRAY OF THREE COILS WITH THREE-PHASE ALTERNATING CURRENTS SIMULATED BY DIRECT CURRENTS

In order to clarify the role of the magnetic field in the three-phase coil system as previously described, Figure 23, three coils were energized with dc according to a schedule of current versus phase angle for the conventional instantaneous values of sinusoidal three-phase currents, and the magnetic field in the center region of the coil system was measured at 31 different locations for each of 12 different phase angles. Figure 202 shows the dc coils. In the center region was mounted a lucite plate having 31 counter-bored ¼-inch diameter sockets for locating the probe of a Bell 120 Gaussmeter (a Hall-effect gaussmeter). The coils were wound on the same form as the rf coils, and they had essentially the same shape. They had each 129 turns, and were connected through rheostats and reversing switches to a dc power source. The currents through the coils were adjusted according to values given by a protractor, marked with three vectors 120 degrees apart, mounted on a square graph (Figure 202) so as to allow the operator to read sine-wave current values for the three coils at specified angles, thus simulating three-phase ac by successive dc values. A compass was used to ascertain that the coils were connected in the proper sense magnetically.
Figure 202. Layout for DC Simulated Three-phase Coils
0 = 260° - VECTOR ROTATION OF CURRENTS

$I_1 = -0.57$ AMPS

$I_2 = -3.95$ '

$I_3 = 3.55$ '

FIELD ROTATION

COIL OUTLINE

3" DIAM.

Figure 203. Sample Data Sheet
The magnetic field measurements were recorded on data sheets as shown in Figure 203, for a complete rotation of the three-phase vectors on the protractor. The data was plotted in various ways, one of which is exemplified in Figure 204. For each data sheet the magnetic field was plotted and a curve was drawn for points around a circle concentric with the center of the coil system. The innermost circle is represented in Figure 204, by curves from two data sheets. Curve 2 is advanced 100 degrees from curve 1, which is the same angular advance as have the currents on the corresponding data sheet.

One can conclude from the investigation that there is a wave of magnetic field strength which travels circularly about the center when coils such as these are excited with three-phase alternating currents.

It was found that there is some second harmonic component in the wave due to unbalance of the system. That is, if opposite each coil, across the three-inch circle, were placed an identical coil carrying current in the opposite angular direction, forming a balanced system, the wave would be more sinusoidal.

A compass needle placed inside the coil array excited by 60 cps three-phase currents rotated rapidly.

Considering rf currents in the three-phase coils, instead of dc, if one were to neglect the complete magnetic field and think of only the magnetic field in this center region, he might incorrectly conclude that there would be an alternating (induced) radial force on a given charged particle in that region; in other words, he might conclude that there is a force field rotating about the center of the
Figure 204. Example of DC Gauss Plot

- • — \( \theta = 160^\circ \)
- \( \times \) — \( \theta = 260^\circ \), but entire curve moved left 100°
coil system in the manner of the force field of the permanent magnet segments. As shown in Chapter I, the induced force field rotates, but these induced electric field vectors do not rotate as spokes in a wheel; they rotate as a family of parallel chords of a circle having its center in common with the coil geometry (such as that largest circle in Figure 203).
REFERENCES


   (NOTE: The section entitled "The Energy Increase for a Collection of Particles" reaches an incorrect conclusion, although the method is sound.)

3. From private communication with Professor M. L. Pool, The Ohio State University, who originated the main points of the argument.


6. Richard F. Post, Radiation Laboratory, University of California Drawing No. 5DL3956; private communication.


11. NRC Equipment Corporation Operating Instructions for Type 9505—164—91 Omegatron. (A partial pressure measuring apparatus of high sensitivity.)

I, James Franklin Holt, was born at Murray City, Ohio, on June 14, 1924. I attended Central High School of Columbus, Ohio, and was granted the Bachelor of Science degree from The Ohio State University in 1949. In 1951, I was granted a Master of Science degree in Physics and Astronomy from the same institution. I was then employed at the Farnsworth Electronics Company, a subsidiary of International Telephone and Telegraph Corporation, in Fort Wayne, Indiana, until 1956 when I returned to The Ohio State University; there I was employed as a research assistant, and later as research associate while pursuing work toward the Doctor of Philosophy degree.
of approach to experiments on fusion reactions were considered in some detail, and many of these were shown to have little potential in future work, according to the investigators. Some of these schemes have since appeared in experimental form at other institutions. The one scheme, investigated here, that seemed to hold most promise is the use of rotating magnetic and electric fields about the axis of a magnetic containing field.

On July 1, 1959, The Ohio State University initiated a modest program for building the mirror magnet and the low power radio-frequency equipment now in use, to accomplish the previously named objectives. Because of the requirement of high dc magnet power, the equipment is located at Don Scott Field, in the Aerodynamics Laboratory of the Department of Aeronautical and Astronautical Engineering.
Chapter I

Theory of Multi-Phase Cyclotron Excitation of Charged Particles

Revolving Magnetic Fields in Cyclotron

Plasma Acceleration

Early in a program of investigating various ways of heating ionized gases, it was recognized that a revolving magnetic field, such as illustrated in Figure 1(a), might force the charged particle toward the magnetic field axis. In addition to a mathematical and graphical solution of the problem, a more straightforward non-mathematical explanation was formulated, which is very useful in understanding many types of cyclotron resonance problems. This explanation proceeds as follows.

The revolving sectors can be replaced by the rectangular moving magnet strips of Figure 1(b). The orbits of charged particles are to be much smaller than the width of the strips, so that a strip edge passes over the orbit in negligible time. Movement of the strip produces a force \( q(v_x \Delta B) \) where \( v_x \) is the velocity of the strip relative to the laboratory, and \( \Delta B \) is the magnetic field in a moving strip. When the particle moves, it has a force on it \( q(v \times B) \), where \( v \) is the particle velocity, and where \( B \) is the total
Figure 1. Magnetic Strips Moving in Ambient Field $B_0$
magnetic field, \( B = B_0 + \Delta B \). Let \( v_0 \gg v \). The moving strips alternately superimpose, upon the particle, radial forces of positive and negative direction. The behavior of the particle is as in the familiar problem of a particle in a constant magnetic field which experiences an additional periodic force; this problem is worked out in the usual texts on electronics. If the alternating vertical forces are not accompanied by change of magnetic field, then the particle orbit, while the particle is in a given strip, is the usual one prescribed by solution of the crossed fields problem with proper initial conditions of velocity and position inserted, which is a cycloid. When rotation of the particle is in synchronism with the time required for a strip to pass over the particle, energy will be given to the particle at a maximum rate.

However, since the alternating forces carry with them the change in magnetic field \( \Delta B \), this increment must be inserted into the value of the magnetic field. Thus, positive increment \( \Delta B \) causes the orbit to be a little smaller than it would be in the \( B_0 \) magnetic field, while negative \( \Delta B \) causes the orbit to enlarge a little, and become greater than it would be in \( B_0 \) magnetic field. Hence, as seen in Figure 2, the orbit climbs or descends, depending upon which way the strips are moving, left or right, providing the particle is acted upon in the cyclotron resonance condition.

Therefore, if a revolving segment magnetic field (Figure 1(a)) could be moved, at adequate angular speed to provide resonance between strips and ions, ions being accelerated by cyclotron resonance could be made to drift toward or away from the center of revolution.
Figure 2. Climbing Orbit in Moving Magnetic Strips
of the magnetic segments by merely revolving the segments one way
or another with respect to the ambient magnetic field $B_0$.

Since mechanical rotation of permanent magnets is out of the
question because of inertia and great angular speeds required in any
practical plasma device, one might employ revolving electromagnetic
fields to approximate the behavior of revolving permanent magnets.
The nearest to practical electromagnetic fields devised to date are
fields of multi-phase currents such as the fields of three-phase
currents of Figure 3(d). It will be shown that such currents pro­
duce a rotating induced electric force field on a charged particle.
By following the same kind of reasoning used above, it may be con­
cluded that drifting of a particle orbit which is in cyclotron
resonance to the currents is not the same as drifting caused by the
moving magnetic strips; instead, drift is in only one direction when
steady cyclotron acceleration is being applied to the particle --
that is, drift is radially outward (toward the currents). If the
currents are causing deceleration by cyclotron resonance the drifting
is radially inward (away from the currents).

Thus, it appears unlikely that cyclotron acceleration of ions by
three-phase currents alone can produce drift toward the mirror field
axis, attributable to the effects described above.

There are many other practical facets to the problem of rotating
cyclotron accelerating electromagnetic fields which have not been
treated in any detail. For instance, there is undoubtedly a variation
of field strength with radius from the containing magnetic field axis;
this variation will play a role in shaping the particle trajectory.
Excited area moves around center. Current flows in same sense in each coil of the area. Coils extend over an entire disc.

(a) Coil Matrix Excited in a Wedge Pattern

(b) Approximation of Matrix by Three-phase Wire Loops

(c) Three-phase Circuits to Encircle Plasma

(d) Three-phase Ring for Encircling Plasma

Figure 3. Evolvement of Three-phase Ring from Consideration of a Rotating Strip Magnet
THREE-PHASE GAS DISCHARGE EXPERIMENTS
IN A MIRROR MAGNETIC FIELD

A Dissertation

Presented in Partial Fulfillment of the Requirements
for the Degree Doctor of Philosophy

by

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The Ohio State University

1962

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Furthermore, this variation will depend upon geometry of the accelerating (rf) currents.

An alternative three-phase ring current assembly would be composed of the three-sided ring of Figure 3(d) plus an identical ring superimposed on that, but reflected about a horizontal through the center of the circle. This kind of three-phase assembly would also have a rotating induced electric field, and a magnetic field revolving about the center. However, the magnetic field would be considerably more symmetrical about the axis of rotation than the magnetic field of the simpler ring of Figure 3(d).
Rotation of Induced Electric Field of a Three-phase Current Array

The revolving magnetic field originally investigated was a wedge, such as might be formed from permanent magnet fields, as described in Figure 1. If such a wedge were to be created using electrical currents, one might build a matrix of small coils as shown in Figure 3(a); by properly exciting this matrix a wedge-shaped field $\Delta B$ could be produced. However, this excitation would entail too much apparatus complexity. The magnetic field produced by such a wedge-shaped bank of coils would be the same as the field produced by a current traversing only the outline of the wedge, providing the coils in the wedge were to be excited by equal currents. By following this line of thought and further simplifying the wedge-shaped outline, as exemplified in Figure 3(a, b, c, d) so as to make it applicable to a vacuum bottle and also to a standard three-phase current source, the simple ring driven at three equally-spaced points was finally devised; this ring would encircle the plasma bottle. The induced electrical field within this ring will differ from that of the simple moving magnetic wedge or strip which was theoretically considered.

The field of this three-phase ring area closely resembles that of the central three-cornered area formed by crossing three large rings of current, Figure 4, as well as of the area surrounded by the three-phase coils actually used shown in Figure 23.
Figure 4. Overlapping Three-phased Current Loops
This section, for mathematical simplicity, describes the electric field of three crossed wires, Figure 5, which approximates the induced electric field in the three-phase ring or crossed rings. It is shown that within the triangle there is an electric vector which rotates at all times in the same sense and with the applied frequency.

Consider wires as in Figure 5, which have total length 2s. Assume no radiation from the wires, because triangle dimensions are much less than one wavelength, and because only the near field is important. Make triangle sides short compared to s, in order that the magnetic field will be nearly constant as the observer moves parallel to s. (This requirement is to simplify the mathematics.) Electric field \( E \) caused by a current change \( \frac{dI}{dt} \) in one wire can be found as follows.

Consider Figure 6; current \( I \) flows in a wire of length 2s, and magnetic field \( B \) is observed at distance \( R \) from the center of the wire. (This figure is an exaggerated view for an observer within the triangle of Figure 5.) Ampere's law (mks rationalized units) is

\[
\frac{dB}{d\tau} = \frac{\mu I}{s} \sin \theta \frac{1}{4\pi R^2},
\]

hence

\[
B = 2\left(\frac{\mu I}{4\pi} \right) \int_{\frac{\theta_2}{2}}^{\frac{\theta_1}{2}} r \, d\theta \frac{1}{R^2} = 2\left(\frac{\mu I}{4\pi} \right) \int_{\frac{\theta_2}{2}}^{\frac{\theta_1}{2}} \sin \theta \, d\theta \frac{1}{R}
\]

\[
= 2\left(\frac{\mu I \cos \theta}{4\pi R} \right) \int_{\frac{\theta_2}{2}}^{\frac{\theta_1}{2}}
\]

\[
B = \left(\frac{\mu I \cos \theta_1}{2\pi R} \right) = \frac{\mu I}{2\pi R} \sqrt{s^2 + R^2}
\]

\[
\text{......................... (1)}
\]
Figure 5. Three-phase Crossed Wires for which Calculation of Induced Electric Field is Performed
Figure 6. Geometry for Determining B and E for Single Wire

Figure 7. Definition of $\phi$, $E_x$, $E_y$
In order to find the electric field caused by a changing current, we use Maxwell's curl equation, $\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$. We differentiate (1) with respect to time and set the result equal to the curl of $\mathbf{E}$ expressed in cylindrical coordinates.

$$\frac{\partial \mathbf{E}}{\partial R} = -\left(\frac{\mu}{2\pi R}\sqrt{s^2 + R^2}\right) \frac{\partial I}{\partial t} \quad \text{........................................... (2)}$$

At a point distance $R$ from the center wire because of symmetry, $\mathbf{E}$ has only the $Z$-component. Since the current is not a function of the point of observation, $\frac{\partial I}{\partial t}$ may be written $\frac{dI}{dt}$.

The induced electric field within the triangle, Figure 5, from a given wire, is to a good approximation only a function of $\frac{dI}{dt}$ and position. Equation (2) is integrated to yield, after removing a constant of integration by use of condition $\mathbf{E} \to 0$ when $R \to \infty$,

$$\mathbf{E} = \left(\frac{dI}{dt}\right) \left(\frac{\mu}{2\pi}\right) \ln\left\{ \frac{s + \sqrt{s^2 + R^2}}{R} \right\} \quad \text{......................... (3)}$$

This is the induced electrical field for Figure 6; now for any point in the triangle of Figure 5, we replace "equals" by "approximately equals".

Consider points in the plane of Figure 5. Total electric field $\mathbf{E}$ is the vector sum of components $E_1$, $E_2$, $E_3$ which represent induced electric fields caused by currents $I_1$, $I_2$, $I_3$, respectively. This vector diagram is shown in Figure 7. To each wire is applied one phase of a three-phase sinusoidal current supply. Arrows depict direction of a positive current change and the direction of electric field caused by that change.

The remaining calculations are to show that $\frac{d\phi}{dt}$ has always the same algebraic sign and to express the total electric field in terms of $I$, $\omega$, $t$, and distance from each wire.
Let $I_1 = I_m \cos \omega t$

$I_2 = I_m \cos (\omega t + 120^\circ)$

$I_3 = I_m \cos (\omega t + 240^\circ)$

\[
\begin{align*}
\text{where } I_m \text{ is the amplitude. These are differentiated and used in (3) to yield the electric field from a } \frac{dI}{dt}; \text{ to take the vector sum of the field components one adds } x-\text{ and } y-\text{ components as represented in Figure 7. Since } R \ll s, \text{ equation (3) can be simplified to}
\end{align*}
\]

\[
E = \left( \frac{\mu}{2\pi} \right) \left( \frac{dI}{dt} \right) \ln(2s/R) \quad \ldots \ldots \ldots \ldots (5)
\]

The rectangular components of the electrical field caused by currents 1, 2, 3, respectively, are, in the plane of these currents,

\[
\begin{align*}
E_{x1} &= \left\{ \left( \frac{\mu}{2\pi} \right) \ln(s/R_1) \right\} I_m \omega \sin \omega t \\
E_{x2} &= \left\{ \left( \frac{\mu}{2\pi} \right) \ln(s/R_2) \right\} \left\{ I_m \omega \sin(\omega t + 120^\circ) \right\} (-\cos 60^\circ) \\
E_{x3} &= \left\{ \left( \frac{\mu}{2\pi} \right) \ln(s/R_3) \right\} \left\{ I_m \omega \sin(\omega t + 240^\circ) \right\} (-\cos 60^\circ)
\end{align*}
\]

\[
\begin{align*}
E_{y1} &= 0 \\
E_{y2} &= \left\{ \left( \frac{\mu}{2\pi} \right) \ln(s/R_2) \right\} \left\{ I_m \omega \sin(\omega t + 120^\circ) \right\} \cos 30^\circ \\
E_{y3} &= \left\{ \left( \frac{\mu}{2\pi} \right) \ln(s/R_3) \right\} \left\{ I_m \omega \sin(\omega t + 240^\circ) \right\} (-\cos 30^\circ)
\end{align*}
\]

The cosine factors come about through taking the horizontal or vertical components of the vectors $E_1, E_2, E_3$.

For brevity let

\[
\begin{align*}
a &= - I_m \omega \left( \frac{\mu}{2\pi} \right) \ln(s/R_1) \\
b &= - I_m \omega \left( \frac{\mu}{2\pi} \right) \ln(s/R_2) \\
c &= - I_m \omega \left( \frac{\mu}{2\pi} \right) \ln(s/R_3), \text{ then the above yields for total } x-\text{component } E_x \text{ and } y-\text{component } E_y,
\end{align*}
\]

\[
\begin{align*}
E_x &= - a \sin \omega t + \frac{b}{2} \sin(\omega t + 120^\circ) + \frac{c}{2} \sin(\omega t + 240^\circ) \ldots \ldots (6)
\end{align*}
\]
\[ E_y = -\frac{\sqrt{3}}{2} b \sin(\omega t + 120^\circ) + \frac{\sqrt{3}}{2} c \sin(\omega t + 240^\circ) \] ............(7)

The object of the following manipulations is to determine whether the rate of change of \( \phi \), meaning \( d\phi /dt \), is always in the same direction. The algebraic sign of this quantity is therefore to be investigated.

Now \( \phi = \cos^{-1}\left(\frac{E_x}{E}\right) = \cos^{-1}\left(\frac{E_x}{\sqrt{E_x^2 + E_y^2}}\right) \) and

\[ \frac{d}{dt} \cos^{-1}\left(\frac{E_x}{E}\right) = -\left[ \frac{d}{dt} \left(\frac{E_x}{E}\right) \right] \sqrt{1 - \left(\frac{E_x}{E}\right)^2} \]

which when expanded is

\[ \frac{d\phi}{dt} = \left(\frac{E_x}{E} \frac{dE_y}{dt} - E_y \frac{dE_x}{dt}\right) / \left(E_x^2 + E_y^2\right) \] .................(8)

The denominator is positive; it is convenient to evaluate it in terms of a, b, c (and t) so that it can be used to check the mathematics.

Use trigonometric identities to expand (6) and (7). Let \( \alpha = \omega t \).

\[ E_x = -a \sin\alpha + b/2 (\sin\alpha \cos 120^\circ + \cos\alpha \sin 120^\circ) \]

\[ + c/2 (\sin\alpha \cos 240^\circ + \cos\alpha \sin 240^\circ) \]

\[ = -a \sin\alpha - b/2 \left(-\frac{1}{2} - \frac{\sqrt{3}}{2} \cos\alpha\right) \]

\[- c/2 \left(\frac{\sin\alpha}{2} - \frac{\sqrt{3}}{2} \cos\alpha\right) \]

\[ E_x = (-a - \frac{b}{4} - \frac{c}{4}) \sin\alpha + \left(\frac{\sqrt{3}}{4} \left[b - c\right]\right) \cos\alpha \] ............(9)

\[ E_y = -b \frac{\sqrt{3}}{2} \sin\alpha + c \frac{\sqrt{3}}{2} \sin(\alpha + 240^\circ) \]

\[ = -\frac{\sqrt{3}}{2} b (\sin\alpha \cos 120^\circ + \cos\alpha \sin 120^\circ) \]

\[ + \frac{\sqrt{3}}{2} c (\sin\alpha \cos 240^\circ + \cos\alpha \sin 240^\circ) \]
\[ E_y = \frac{\sqrt{3}}{2} \left\{ -b\left(\frac{-\sin\alpha}{2} + \frac{\sqrt{3}}{2}\cos\alpha\right) + c \left(\frac{-\sin\alpha}{2} - \frac{\sqrt{3}}{2}\cos\alpha\right) \right\} \]

\[ E_y = \frac{\sqrt{3}}{2} \left\{ \frac{(b-c)}{2} \sin\alpha - \frac{\sqrt{3}}{2} (b + c) \cos\alpha \right\} \] ......(10)

\[ E_x^2 + E_y^2 = (\frac{-a - \frac{b}{4} - \frac{c}{4}}{2})^2 \sin^2\alpha + \left(\frac{\sqrt{3}}{4}\left[b - c\right]\right)^2 \cos^2\alpha \]

\[ + 2\left(\frac{-a - \frac{b}{4} - \frac{c}{4}}{2}\right) \left(\frac{\sqrt{3}}{4}\left[b - c\right]\right) \sin\alpha \cos\alpha \]

\[ + \frac{3}{4}\left\{ \left[b - c\right]^2 \frac{\sin^2\alpha}{4} + \left(b + c\right)^2 \frac{3}{4} \cos^2\alpha \right\} \]

\[ - \frac{\sqrt{3}}{2} \left(b - c\right) \left(b + c\right) \sin\alpha \cos\alpha \} \] ......(11)

One can see from a vector diagram that, at the center of the triangle, vector \( \mathbf{E} \) rotates at constant rate \( \frac{d\alpha}{dt} = \omega \), and \( \mathbf{E} \) has a constant magnitude. To check the mathematics, let \( a = b = c = 1 \). In this case,

\[ \mathbf{E} = \sqrt{E_x^2 + E_y^2} = \frac{3}{2} \]. This is the value to be expected from vector drawings at the center of the triangle, of three-phase components \( E_1, E_2, E_3 \), when the individual field magnitudes are unity.

We now differentiate (9) and (10) to obtain \( \frac{dE_x}{dt} \) and \( \frac{dE_y}{dt} \) so that (8) may be expanded further.

\[ \frac{dE_x}{dt} = \omega \left\{ \left(-a - \frac{b}{4} - \frac{c}{4}\right) \cos\alpha - \left(\frac{\sqrt{3}}{4}\left[b - c\right]\right) \sin\alpha \right\} \] ......(12)

\[ \frac{dE_y}{dt} = \omega \left\{ \frac{\sqrt{3}}{2} \left[ \frac{(b-c)}{2} \cos\alpha + \frac{\sqrt{3}}{2} (b + c) \sin\alpha \right] \right\} \] ......(13)
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\[ E_x \frac{dE_y}{dt} - E_y \frac{dE_x}{dt} = -\omega \left\{ (-a - \frac{b}{4} - \frac{c}{4}) \cos\alpha - \frac{\sqrt{3}}{4} \left[ b - c \right] \sin\alpha \right\} \]

(times) \( \left\{ \frac{(b - c) \sin\alpha - \sqrt{3}}{2} \left[ b + c \right] \cos\alpha \right\} \frac{\sqrt{3}}{2} \]

+ \( \omega \left\{ \frac{\sqrt{3}}{2} \left[ \frac{(b - c) \cos\alpha + \sqrt{3}}{2} \left[ b + c \right] \sin\alpha \right] \right\} \)

(times) \( \left\{ (-a - \frac{b}{4} - \frac{c}{4}) \sin\alpha + \left( \frac{\sqrt{3}}{4} \left[ b - c \right] \right) \cos\alpha \right\} \).

When multiplied out and expressed in simpler form, \( E_x \frac{dE_y}{dt} - E_y \frac{dE_x}{dt} \)

\[ = \frac{\sqrt{3}}{2} \omega \left\{ \left[ a + \frac{b}{4} + \frac{c}{4} \right] \left( -\frac{\sqrt{3}}{2} \left[ b + c \right] \right) + \frac{\sqrt{3}}{8} (b - c)^2 \right\} \left( \cos^2 \alpha + \sin^2 \alpha \right) \right\}; \]

\[ E_x \frac{dE_y}{dt} - E_y \frac{dE_x}{dt} = \frac{\sqrt{3}}{2} \omega \left\{ \left[ a + \frac{b}{4} + \frac{c}{4} \right] \left( -\frac{\sqrt{3}}{2} \left[ b + c \right] \right) + \right. \]

\[ \left. + \frac{\sqrt{3}}{8} (b - c)^2 \right\} \] .................................(14)

Substitute (11) and (14) into (8) to obtain an expression for \( \frac{d\phi}{dt} \).

\[ \frac{d\phi}{dt} = \frac{\sqrt{3}}{2} \omega \left\{ \left[ a + \frac{b}{4} + \frac{c}{4} \right] \left( -\frac{\sqrt{3}}{2} \left[ b + c \right] \right) + \frac{\sqrt{3}}{8} (b - c)^2 \right\} \]

\[ \left\[ \frac{3}{16} (b - c)^2 + \frac{9}{16} (b + c)^2 \right\] \cos^2 \alpha \]

+ \left\{ \left[ a + \frac{b}{4} + \frac{c}{4} \right]^2 + \frac{3}{16} (b - c)^2 \right\} \sin^2 \alpha

- \sqrt{3} \left[ \frac{1}{2} (b - c) \left( a + \frac{b}{4} + \frac{c}{4} \right) + 2 \left( b^2 - c^2 \right) \right] \sin\alpha \cos\alpha

.................................(15)

The denominator is positive because of the quadratic form. Upon inspection one finds that the numerator always is negative regardless of values of \( a, b, \) or \( c \).
Therefore, field vector $E$ rotates about the center of observation and rotates always in the same sense, at any point inside the triangle. The frequency of rotation must be the frequency $(\omega/2\pi)$ of the applied currents, but the angular speed can vary during one cycle; this is evident from the $\sin \alpha \cos \alpha$ term in the denominator of (15).
Comparison of Voltage and Current

for Particle Acceleration

In the preceding section a certain induced electric field $E$ was shown to exist in the vicinity of a wire carrying a changing current $I$, and the value of induced electric field $E$ was given in equation (3). It should be possible to provide the same magnitude of electric field over a limited space by the presence of charged electrodes. This section deals with the voltages required on a certain set of electrodes that will give a reasonable approximation to the electric field of two parallel wires which each carry a sinusoidal current $\frac{I}{2}$. See Figure 8.

Using equation (3) we find at the center of the parallel wire geometry the induced electric field $E_1 = \frac{\mu_0}{2\pi} \frac{dI}{dt} \ln (\cot \theta + \sec \theta)$.  

We now consider what voltage $V$, as indicated on the electrodes of the figure, will yield the same field magnitude. No attempt is made to determine how nearly the overall $E_2$ field from the voltages approximates that from the currents. It is apparent, however, that in both (a) and (b), over a small region around the center $E$ is nearly uniform in direction and magnitude, at a given time. We consider points in the plane and at center of the wire arrangement (a), and at the center of the geometry of electrodes (b).

Let $I = I_m \sin \omega t$, $\frac{dI}{dt} = \omega I_m \cos \omega t$.

\[ E_1 = \left\{ \frac{\mu_0}{2\pi} \omega I_m \ln (\cot \theta + \sec \theta) \right\} \cos \omega t \]
Figure 8. Current (above) and Voltage (below) Arrays that Produce the Same E Field Magnitude at Mid-point
\[ T_m \text{ is a current amplitude: let } F_m = \left\{ \omega T_m \ln(\cot \theta + \sec \theta) \right\}^{24} \]

then \( F_1 = F_m \cos \omega t \). In the electrode arrangement it is desired to produce this same \( E \) magnitude; that is, require \( F_1 = E_2 \) and find a corresponding voltage-to-current ratio \( \frac{V_m}{I_m} \); \( V_m \) refers to amplitude of voltage on the electrodes structure while \( I_m \) refers to amplitude of current in the wires; let \( V = V_m \cos \omega t \). The electric field in volts/meter of a pair of line charges as in Figure 8(b) is, at the center, \( F_2 = \frac{\sqrt{2} Q}{\pi \varepsilon S^2} \) \hspace{1cm} (18)

\( Q = \) total charge of an electrode, \( \varepsilon = \) dielectric constant, in mks rationalized units.) Capacity per unit length of two very long parallel cylindrical conductors is, in farads/meter,

\[ C = \frac{\pi \varepsilon S}{\ln\left\{ \frac{S}{2r} + \sqrt{\left(\frac{S}{2r}\right)^2 - 1} \right\}} \hspace{1cm} (19) \]

where \( \varepsilon = \) dielectric constant, \( S = \) separation of cylinders, \( r = \) radius of each conductor. For length \( S \), capacity \( C \) of the array is

\[ C = \frac{\pi \varepsilon S}{\ln\left\{ \frac{S}{2r} + \sqrt{\left(\frac{S}{2r}\right)^2 - 1} \right\}} \hspace{1cm} (19) \]

Now \( V = \frac{Q}{C} \). Use \( Q \) from (18) and \( C \) from (19).

\[ V = \frac{E_2 S}{\sqrt{2}} \ln\left\{ \frac{S}{2r} + \sqrt{\left(\frac{S}{2r}\right)^2 - 1} \right\} \hspace{1cm} (20) \]
Insert $E_1$ for $E_2$ from equation (17);

$$V = \frac{\mu S \ln(\cot \theta_1 + \sec \theta_1) \ln \left\{ \frac{S}{2r} + \sqrt{\left(\frac{S}{2r}\right)^2 - 1} \right\} \omega I_m \cos t}{2\pi \sqrt{2}} \cdots (21)$$

$$\frac{V_m}{I_m} = \frac{S \ln(\cot \theta_1 + \sec \theta_1) \ln \left\{ \frac{S}{2r} + \sqrt{\left(\frac{S}{2r}\right)^2 - 1} \right\} \omega}{2\pi \sqrt{2}} \cdots \cdots \cdots (22)$$

For example, suppose $S = .15$ meter = 1 foot, $r = .01$ meter, geometry as indicated in Figure 8 and $\omega = 2\pi \times 1.86 \times 10^6 \text{ sec}^{-1}$.

The $\theta_1 = 45^\circ$ and

$$\frac{V_m}{I_m} = \frac{4\pi \times 10^{-7} \times 0.15 \times \ln(1 + \sqrt{2})\ln(7.5 + \sqrt{55.25}) \times 2\pi \times 1.86 \times 10^6}{2\pi \sqrt{2}}$$

volts \quad = \quad 0.59 \quad \text{volts ampere} \quad \frac{\text{ampere}}{\text{ampere}} .$$

Conclusion: when $S = 1$ foot the electric field at center is the same magnitude whether $\frac{1}{2}$ ampere flows at angular frequency $2\pi \times 1.86 \times 10^6 \text{ sec}^{-1}$ in each wire or whether 0.59 volts appears across the electrodes, also at this angular frequency. (Questions about penetration into a plasma are not asked here.)

**Ion Acceleration Estimate**

Assume that the induced electric field within the three-phase ring Figure 3(d), is the same as the induced electric field within the triangle of Figure 5 when the ring can be inscribed inside the triangle; then one can use equation (5) and the theory of cyclotron resonance heating to predict approximately the behavior of the current ring as a plasma heater. Refer to Figures 9 and 10. The following assumptions are made:
(I_1' is of same magnitude as I_1 but 30° ahead in phase.)

(a) Long Crossed Current Lines
(b) Current Triangles
(c) Current Rings

Figure 9. Some Configurations of Currents which Yield Approximately the Same Fields in the Central Volume
Figure 10. Geometry for Field Calculations

\[ E_{\text{min}} = \frac{n \omega}{2 \pi} I_m(1.70) \]

\[ E_{\text{max}} = \frac{n \omega}{2 \pi} I_m(2.52) \]

Figure 11. Schematic for Exciting Three-phase Current Ring
1. Electric field inside the ring assembly, Figure 9(c), is nearly equal to the field inside the crossed wires (a).

2. Point P in the plane of one triangle, Figure 10(a) represents an average point; that is, the cylindrical plasma volume enclosed by the two rings times the ion density times the power per ion given at point P equals the total power absorbed by the gas from the current rings.

3. The rotating induced electric field within the current rings has the same effect on the ions as two sinusoidally varying electric vectors orthogonal to each other at point P; hence the conventional single-phase cyclotron resonance heating formula is applicable to this rotating field problem by adding energies imparted by each component of the rotating field.

Calculations of heating were carried out for the conditions
a) all ions are in phase with the applied fields, b) all initial ion energies are 7 ev, c) containing magnetic field B = 2410 gauss, d) frequency of applied rf fields f = 1.86 megacycles/sec, e) density of ions is $10^{12}$/cm$^2$.

Figure 11 shows how the current rings are to be driven, schematically.

Magnitude of each component of the induced electric field is calculated for the given conditions, and substitution of these magnitudes into the cyclotron resonance heating formula, Glasstone and Lovberg equation 5.26, leads to a value for energy given to one ion in one rotational cycle. Total power imparted to ions at a given density is then readily obtained.

A certain size and shape of the plasma container and current rings is specified in order to calculate skin power losses in the current rings.
Magnitude of the electric field associated with a given wire is expressed in equation (3), which gives for the three wires of Figure 10(a) at point P,

\[ E_2 = \frac{\mu}{2\pi} \left| \frac{dI_1}{dt} \right| \ln \left\{ \frac{s + \sqrt{s^2 + R_1^2}}{R_1} \right\} = \frac{\mu \omega}{2\pi} (1.13) I_m \ldots \ldots \ldots (23) \]

\[ E_1 = E_3 = \frac{\mu}{2\pi} \left| \frac{dI_2}{dt} \right| \ln \left\{ \frac{s + \sqrt{s^2 + R_2^2}}{R_2} \right\} = \frac{\mu \omega}{2\pi} (1.96) I_m \ldots \ldots (24) \]

In calculating the field at point P we ignore the contribution to the field by the adjacent current ring.

From the geometry, Figure 10(a), \( R_1 = R_3 = \frac{\sqrt{3}}{12} \), \( R_2 = \frac{\sqrt{3}}{6} \).

A time vector diagram of \( I_1, I_2, \) and \( I_3 \) plus the above field magnitudes is then used to construct two orthogonal vectors in space which are the total induced electric field at two particular different times. One vector is the semi-minor axis and the other vector is the semi-major axis of an elliptical envelope, as shown in Figure 10(b). Total electric field vector \( \mathbf{E} \) rotates about point P inside the envelope.

Figure 10(b) states the magnitudes of the two orthogonally-directed semi-axes; these magnitudes are used in equation 5.26, page 140 of Glasstone and Lovberg, separately to yield the energy imparted to an ion by the two components described in assumption 3 above.

This equation is \( \Delta W_\perp = a r_g \) where \( \Delta W_\perp \) is the energy in electron volts gained by a singly-charged ion in one cycle, \( \oint \mathbf{E} \cdot d\mathbf{s} \); \( a \) is defined as \( E_{\text{max}} \), where \( E_{\text{max}} \) is the maximum induced electric
design and installation of dc power connections. The author is appreciative of the photographic prints and Figures which were done by the Department of Photography.
field strength at the cyclotron frequency, and \( r_g \) is the radius of gyration of the particle which is \( 2.2 \times 10^{-3} \) meter for deuterons of 7 ev in a 2410 gauss magnetic field.

Since there are two induced electric fields in phase with the particle orbit, the energy integral \( \Delta W_\perp \) of the deuteron in one cycle is

\[
\Delta W_\perp = 2.2 \times 10^{-3} \text{ meter}\pi \left\{ \frac{\mu_0}{2\pi} (1.70) I_m + \frac{\mu_0}{2\pi} (2.52) I_m \right\}
\]

\[
\frac{\text{electron volts}}{\text{meter-ampere cycle}} = 1.1 \times 10^{-2} \frac{I_m}{\text{ampere-cycle}} \text{ electron volts.}
\]

\( I_m \) is the current magnitude in one current ring corresponding to the triangle of Figure 10(a).

The power imparted to the deuterons is thus,

\[
P_i = N_i f V \left\{ 1.1 \times 10^{-2} I_m \times 1.6 \times 10^{-19} \right\} \text{ joules ampere}
\]

where \( N_i \) = ion density in number of ions/meter\(^3\).

\( f \) = frequency of applied currents in cycles/second.

\( V \) = estimated volume over which the applied currents are effective.

In this example, \( N_i = 10^{12}/\text{cm}^3 \), \( f = 1.86 \times 10^6/\text{sec} \); let the volume \( V \) enclosing the heated ions be a cylinder six inches diameter, three inches long surrounded by the current rings, and let \( I_m = 50 \) amperes; then \( P_i = 230 \) watts.

The total current magnitude entering any terminal of the Figure 12 assembly is in this case 100 amperes.
Figure 12. Relative Dimensions of Heating Volume and Rings in Calculations for Table 1
Table 1 shows the results for an ion density $10^{12}$ ions/cm$^3$; also shown are results of calculations of resistance losses within the ring conductors. These resistance losses were calculated as in the next paragraph. (Note that these loss calculations represent an ideal situation. The actual coils used, Figure 23, were found to yield a stronger induced field for a given power supplied; this comes about from the problem of impedance matching.)

Consider the current rings of Figure 12, of radius $r$ and conductor diameter $d$, where a certain ratio $(d/r)$ is specified. The equivalent conducting thickness of a conductor is the skin depth given by $\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} = 6.6 \times 10^{-2}/\sqrt{f}$, for copper. Units are rationalized mks, frequency in cps, $\sigma$ = conductivity $= \frac{1}{\rho}$ = 1/resistivity. The resistance of one ring is

$$R_s = 2\pi r \rho / \pi d \delta = 2(r/d) \rho / \delta = 2(r/d) \rho \sqrt{f} / (6.6 \times 10^{-2}) \text{ohms.}$$

Resistivity is $1.77 \times 10^{-8} \text{ohm-meter}$, hence

$$R_s = 0.536 (r/d) 10^{-6} \sqrt{f} \text{ ohms when } f \text{ is the number of cps.}$$

When $(r/d)$ is specified, size of the ring is of no concern, and power loss in the ring is dependent only on current through it. Use of the above formula for the conditions of Table 1 gives the values of resistive power losses listed.
TABLE 1.—Characteristics for Power Absorption by Hydrogen Ions Inside Three-phase RF Currents for Heating Assembly of Figure 12, and at Point P of Figure 10(a), at 10^{12} ions/cm^3.

<table>
<thead>
<tr>
<th>r (cm)</th>
<th>I_{mt} (amps)</th>
<th>f (cps)</th>
<th>\Delta W_1 (ev/ion-cycle)</th>
<th>P_1 (watts)</th>
<th>P_s (watts)</th>
<th>P_t (watts)</th>
<th>R_e (ohms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>10</td>
<td>1.86 \times 10^6</td>
<td>0.011</td>
<td>2.30</td>
<td>0.19</td>
<td>2.50</td>
<td>0.050</td>
</tr>
<tr>
<td>31.6</td>
<td>11</td>
<td>23</td>
<td>1.90</td>
<td>250</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>1.1</td>
<td>230</td>
<td>19</td>
<td>250</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>316</td>
<td>11</td>
<td>2,300</td>
<td>190</td>
<td>2,500</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1,000</td>
<td>110</td>
<td>23,000</td>
<td>1,900</td>
<td>25,000</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Symbols:  
- \( I_{mt} \): peak rf current into any one terminal of the Figure 12 assembly, \( 2 \times \) peak rf current in any \( 120^\circ \) section of above assembly.  
- f: frequency of applied rf current.  
- \( \Delta W_1 \): energy imparted to an ion inside the heated volume by one cycle of applied rf current.  
- \( P_1 \): power absorbed by the heated volume of ions.  
- \( P_s \): power dissipated as heat in rings.  
- \( P_t \): total power consumed.  
- \( R_e \): equivalent resistance of the assembly between any two terminals \( \equiv P_t / I_{mt}^2 \).  
- r: radius of current ring assembly, \( 4/3 \) plasma radius.
Temperature attainable depends mainly on power input to the plasma and power losses of the plasma. When these two rates are equal the temperature is stabilized. When average ion containment time is \( t_c \) seconds, average ion energy is \( W_i \) electron volts, ion density is \( N_i \) ions/cm\(^3\), and volume of ions is \( V \) cm\(^3\), the power loss in watts caused by ion escape is

\[
P_e = N_i V W_i 1.62 \times 10^{-19} / t_c \tag{30}
\]

Suppose escape is the only power loss; suppose the total contained volume is a cylinder 6 inches diameter and 12 inches long, or \( V = 5.55 \times 10^3 \) cm\(^3\); also suppose \( t_c \) is 1 millisecond, and \( P_e \) is 200 watts. When the above equation is solved for ion energy, \( W_i = 2,200 \) ev.

Electromagnetic radiation resulting from gyration of electrons in the dc magnetic field\(^5\) will be less than 1 watt when the mean electron energy is 2,200 ev and the dc field is 2,400 gauss; therefore, this source of power loss would not be serious, even if the electron temperature were brought up to equal the ion temperature.

The observed heating of ions still in the 0—10 ev neighborhood as estimated from spectroscopic observations, would not approach the above calculated value; there are various explanations for this. The achieved ion density is undoubtedly much less than that used in the calculations; there is undoubtedly some shielding of the applied fields by electron currents in the plasma; there is also the problem of getting a highly disocciated molecular gas to form a highly ionized atomic gas so as to achieve the cyclotron resonance heating.
CHAPTER II

EXPERIMENTATION

Apparatus

General Description

Figure 13 is a perspective sketch of the dc magnet, rf coils and electrodes for exciting the gas, and gas chamber. All information presented here was taken using a three-inch straight Pyrex glass pipe gas chamber, rather than with the tapered glass bottle of Figures 14, 15, and 22.

A mirror magnetic field having a mirror field ratio 3.5/1 and a maximum end field of 11,900 gauss, is set up by the dc magnet which is powered from a dc motor-generator operated by personnel of the Aerodynamics Laboratory. Ionization of gas is caused by rf energy applied to coil and electrode elements which are located about the axis of the gas chamber at the central plane which is perpendicular to the axis. (The effect of electrodes was of interest because of the outward drifting caused by cyclotron resonant currents. Comparison of effect of coils, electrodes and coils plus electrodes was desired.) Ionized gas touches the glass walls at the central portion, and tapers down in two cones toward the maxima of dc magnetic field,
Figure 13. APPARATUS LAYOUT FOR 3Ø EXPERIMENTS
Figure 14. DC Magnet (foreground) and Magnet Current Disconnect Switch (upper left) Before Completion of Electrical and Water Connections.

Figure 15. Side View of DC Magnet and Supporting Oak Bench with Rails
where it occupies a minimum diameter; it flares out at the magnet ends. The envelope of ionization thus follows the contour of the dc magnetic flux.

A crystal-controlled rf oscillator-amplifier system supplies three-phase or single-phase power to an array of three coils and three electrodes at the central plane. This system provides fixed-frequency, fixed-phase, variable-amplitude rf power up to a maximum of 4 kilowatts to the load circuits. Most of this power is dissipated as heat in the water-cooled load coils.

The three six-inch diameter open-ended transmission lines may be considered as capacitors resonating with their respective load coils at the crystal frequency, because they are considerably less than a quarter-wave long.

Evacuation of the gas chamber to $2 \times 10^{-6}$ mm mercury is accomplished by a conventional three-stage oil diffusion pump with liquid nitrogen trap. A steady gas influx is controlled by a needle valve.

Pictures are taken usually from the end glass or quartz windows.

DC Magnet

The dc mirror magnet is pictured in Figures 14—17. Pertinent specifications are given in Table 2. National Electric Coil Division of McGraw Edison Company, Columbus, Ohio, fabricated the copper windings; see their drawings reproduced in Figures 18—21. Figure 22 is a layout drawing of the mounting mechanism. The OSU Physics Shop constructed the oak bench, the mounting mechanism, and assembled the individual coils into the mirror magnet as used in all experiments to date.
Figure 16. View from Above of DC Magnet Water Hoses, Pancake Series Connectors, Flexible DC Cables (center right), and Coaxial Six-inch RF Lines (center).

Figure 17. RF Assembly and Six-inch Coaxial Lines (center), RF Rack (left), and One Solenoid of the DC Magnet (right).
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TABLE 2.—DC Magnet Specifications

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<td><strong>Conductor:</strong></td>
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<tr>
<td><strong>Pancake:</strong></td>
</tr>
<tr>
<td><strong>Geometry:</strong></td>
</tr>
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</table>

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<th>Electrical</th>
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<tr>
<td><strong>Resistance:</strong></td>
</tr>
<tr>
<td><strong>Current:</strong></td>
</tr>
<tr>
<td><strong>Magnetic field:</strong></td>
</tr>
<tr>
<td><strong>Inductance:</strong></td>
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<th>Cooling</th>
</tr>
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<tr>
<td><strong>Water supply:</strong></td>
</tr>
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<td><strong>Temperature rise:</strong></td>
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<td><strong>Attraction:</strong></td>
</tr>
<tr>
<td><strong>Distortion of end plates:</strong></td>
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</tbody>
</table>
There are 24 separate epoxied "pancake" coils consisting of \( \frac{1}{2} \times \frac{1}{2} \)-inch high-conductivity copper conductor, having a \( \frac{1}{4} \)-inch diameter water channel, wound in two layers. Cool water flows into the outer rim of a pancake, spirals to the center turn, crosses over to the next layer, and spirals back out to be recooled. Electrical connection of the 24 pancakes is independent of the cooling water connections.

Position of pancakes can be altered by moving supporting wooden blocks and by inserting separator blocks if needed. The rail mounting has been entirely satisfactory for manipulating the magnet coil sections.

In all experiments the 12-pancake mirror coils are 14-3/8 inches apart, from one \( \frac{1}{2} \)-inch aluminum end plate to the other; each of these coils is 14 inches long excluding aluminum end plates.

Magnet current is controlled by a remote (human) operator, and a change in magnet current is requested by the experimenter over interphone. No automatic current control or regulation exists. DC ripple is much less than 1%, and the generator operator can manually hold regulation to \( \pm 5 \) amperes at 500 amperes for any extended time. The generator is shut down by opening field windings of motor and generator. Connection to the dc generator is never broken when the magnet current is flowing. (A 500-ampere magnet current broken by the dc circuit breaker will cause a damaging arc in the breaker as well as a 1000-volt surge across the magnet.)
Figure 18. National Electric Coil Drawing No. 1A1568
**COPPER SPECIFICATIONS:**

- 100%, 360% B. C. O.F.H.C. COPPER WITH .200" I.D. HOLE
- 1/16" MINIMAL RADIUS ON CORNERS
- TOLERANCES: 4.002" ON OUTSIDE DIMENSIONS,
  3.002" ON INSIDE DIAMETER

Wire to be furnished on 34" DIAMETER CENTERS MINIMUM. Coils to be annealed after coiling.

60 FOOT MINIMUM LENGTHS - 100 FOOT LENGTHS PREFERRED.

---

COUNTERBORE .375" DIA. - 3/4" DEEP
SILVER SOLDER TUBING IN PLACE.

SILVERPLATE LEADS BACK 2-1/2" FROM END.

STENCIL

CROSS OVER MUST BE HELD WITHIN 90°

START LEFT

SEE ED 5M A1568

---

12 VOLT OPERATION

---

Figure 19. National Electric Coil Drawing No. 91926
**Copper Specifications**

0.008" x 0.008" O.D. Cu. O.F.N.R. Copper with 0.006" I.D. Hole

1/16" minimum radius on drivers.

Tolerances: 0.003" on outside dimensions.

3.000" on inside diameter.

Wire to be furnished on 34" diameter centers minimum. Coils to be annealed after coiling.

50 foot minimum lengths - 100 foot lengths preferred.

Copper - annealed after coiling.

wire to be furnished on 34" diameter centers minimum. Coils to be annealed after coiling.

50 foot minimum lengths - 100 foot lengths preferred.

Figure 20. National Electric Coil Drawing No. 91927
Figure 21. National Electric Coil Drawing No. 91928
Figure 22. Layout of DC Magnet Mounting Mechanism
Radio Frequency System

Three rf load coils and three electrodes are mounted at the center plane of the dc magnet as shown in Figures 13, 23, and 24. The coils are water-cooled by softened well water supplied through Tygon tubing. Approximately 8 feet of Tygon per coil is used in such a manner that all coils have the same loading from water electrical conduction. Teflon-E bars and fiber clamps hold the coils rigidly on the 3-inch Pyrex gas chamber.

The electrodes are comb-shaped pieces of brass each 1 x 2 inches; slots of the comb are to minimize shielding of the rf magnetic field from the gas chamber. A sliding Teflon-E ring holding the electrodes 120 degrees apart permits changing mechanical phase of electrodes relative to coils plus or minus 20 degrees.

Table 3 gives major characteristics of the entire rf equipment, while Figure 25 is the block diagram. Class C amplifiers are used throughout, with no negative feedback control or tuning; coupling between load elements is a factor in tuning procedure. In some three-phase rf devices phase drifting has been a source of trouble, partly because of required phase accuracy, and partly because of heating of certain parts of the equipment. In this apparatus, no serious drift in phase adjustment takes place, since temperature rise of the rf coils is limited by water cooling, and the resonating capacitor (transmission line) has a large cooling area which does not heat appreciably. Measurement of phase is within plus or minus 3 degrees by means of a Tektronix 517A oscilloscope. A special high-voltage rf attenuator had to be constructed for the oscilloscope.
Figure 23. Three-phase Coil and Electrode Positions
Figure 2h. Three-phase Load Coils (top, bottom), Three-phase Electrodes (center), and Pyrex Chamber (center).
## FIGURES

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UNIVERSITY MICROFIMS, INC.
### TABLE 3.—Specifications of RF Equipment

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
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<tbody>
<tr>
<td>Frequency:</td>
<td>1.86 or 4.15 mc., crystal-controlled. Maximum frequency 10 mc., could be raised to 30 mc. after load circuit alterations.</td>
</tr>
<tr>
<td>Phasing of Outputs:</td>
<td>1, 2, or 3-phase; depends upon phase of drive connections to final class C amplifiers; 2200-ohm delay lines determine driving phases.</td>
</tr>
<tr>
<td>Output power:</td>
<td>0—3 kw total from 833-A amplifiers; 0—1 kw total from 813 amplifiers. 0—4 kv peak rf voltage across load coils; 0—2 kv peak rf on electrodes.</td>
</tr>
<tr>
<td>Output waveform:</td>
<td>Pure sine wave.</td>
</tr>
<tr>
<td>Power source:</td>
<td>3-phase 60 cycle 110 v, 40 amps ac.</td>
</tr>
</tbody>
</table>
NOTE: ALL BLOCKS ARE CLASS C AMPLIFIERS EXCEPT AS INDICATED.

Figure 25. Block Diagram of RF System
The crystal oscillator is a standard Pierce type which needs no tuned circuits; to change its oscillating frequency it is only necessary to change the crystal.

To change operation of the amplifiers to a new frequency one must change plug-in coils and capacitors as indicated on the schematics by arrows; see Figures 26—29. Plug-in units are on hand for 4.15 mc and 1.86 mc. Each six-inch coax line in the rf load circuits must be the length to very nearly resonate at the operating frequency with the three-phase load coil.

Conventional class C amplifiers are used throughout. The 6AQ5's serve as buffers to drive 2200-ohm delay line sections (Columbia Technical Corp. HH-2000) which approximately determine the 120 degree phase shifts for three-phase operation. For other phases, different (plug-in) lines are needed. Operating conditions of the 6AQ5's were selected to provide a 2200-ohm output impedance to the delay line. The terminating circuits of the lines are tuned to resonate at the crystal frequency, and under this condition termination is a resistive 2200 ohms. Some slight phase adjustment is possible by tuning at either end of the line, in case a delay line is not precisely the correct length.

A balanced output circuit in the 6L46 amplifiers permits two output signals to be obtained. Both of these are needed in neutralizing and driving the 833-A's, but either may be utilized to drive the 813's. A plug-in capacitor must be installed opposite the side of the 6L46 output circuit that is connected to the 813's, so as to maintain rf voltage balance across the 6L46 plate coil. This plug-in
THREE-PHASE RF GENERATOR FOR COILS

Figure 26. Schematic Diagram, Three-phase RF Generator for Coils
Figure 27. Schematic Diagram, High Voltage Supply and Control Circuits for 833-A's
Figure 28. Schematic Diagram of Meter Panel in 833-A Rack
Figure 29. Schematic Diagram of 813 Circuits for Electrode Excitation
capacitor must equal the input capacity of the 813 amplifier including the coaxial connecting cable. Figures 30, 31, and 17 show the backs of the 833-A rack, 813 rack, and front of 833-A rack, respectively.

Output 833-A amplifiers utilize a variable-capacitance pi-network for impedance matching as well as for making slight tuning corrections for non-resonance in load tank circuits.

Construction of the rf equipment was done by students on campus; however, the following power supplies were purchased:

Kepco Model 1250B, 0-1000 vdc, 0-0.5 amperes; for 6146 amplifiers, plate voltage.

Lambda Model C-481M, 125-325 vdc, 0-400 ma; for grid bias on 833A's and 813's.

Atomic Instrument Co. (modified), 230 vdc and 150 vdc for regulated screen voltage and crystal oscillator plate voltage.

Vacuum Apparatus

Pyrex double-tough glass pipe of 3-inch nominal size is used throughout the vacuum chamber. Standard aluminum Pyrex flanges join the various fittings. Flat neoprene gaskets with no grease are used for all Pyrex pipe seals. There are no gaskets located within the three-foot length of the gas chamber. On a "T" at the geographic south end of the chamber is a four-inch diameter glass window, and a four-inch diameter quartz window is similarly placed at the other end, so that one can see through the entire gas volume.

At the geographic north end, as indicated in Figure 32, and pictured in Figure 33, a needle valve controls the gas influx so that any pressure from 0.1 micron to 1000 microns can be manually
Figure 30. Rear View, 833-A Rack

Figure 31. Rear View, 813 Rack
Figure 32. Block Diagram of Vacuum System
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Figure 33. Needle Valve (upper left) and Vacuum Gauge Attachments to Pyrex T

Figure 34. Oil Diffusion Pump (right) and High Vacuum Valve (upper center)
controlled. Pumping is maintained at all times during plasma experiments. Pressure can be measured at either end of the gas chamber. At 100 microns the pressure differential end-to-end is 10 microns. Baffles at gauges nearest the gas inlet prevent direct flow of gas onto the gauge orifice. A deuterium gas cylinder feeds into an ordinary hydrogen gas regulator; the deuterium gas line and regulator is in series with the line from a hydrogen cylinder, in order that the deuterium line can be completely purged with hydrogen before operating with deuterium. To operate with deuterium, the procedure is to purge the line and the chamber with hydrogen, then pump line and chamber down for several minutes before letting in deuterium.

At the south end the Pyrex pipe "T" connects to a bellows screened with bronze wire which keeps gaseous discharge out of the pump. A six-inch oil diffusion pump made by the OSU Physics Shop, with a six-inch liquid nitrogen trap attaches there through a three-inch high-vacuum gate valve; see Figure 34. (The diffusion pump could have been smaller; however, this one was used because it was at hand and could be relied upon.)

The vacuum can always be pumped down to $2 \times 10^{-6}$ mm mercury in 45 minutes or less when all seals are proper and when no gas is being let in. One-half hour is the usual time for pumping down when the diffusion pump does not need outgassing. Dow Corning 703 diffusion pump oil is used (Dow Corning Corporation, Midland). A rotary Cenco Hypervac forepump brings the pressure to 20 microns from one atmosphere in 15 minutes. This pump was checked for ultimate pressure,
and it provided $5 \times 10^{-4}$ mm mercury pressure when pumping only from a Pirani gauge with no rubber connections. Ultimate pressure of the oil diffusion pump without baking was measured at $1.8 \times 10^{-6}$ mm.

The ionization gauge tubes VG-1-A operate into a Consolidated Vacuum GIC-110 circuit, and the Consolidated Vacuum Pirani gauge tube into a Consolidated Vacuum GP-105 circuit. Leaks causing several microns pressure rise can be located by using the acetone painting procedure, observing an indicated pressure shift on the Pirani gauge meter.

Electron Beam Device

In order to observe the direction, magnitude and timing of accelerating forces on a charged particle within the Pyrex gas chamber and in the vicinity of the three-phase rf elements, an electron beam was provided by a gun removed from a 5BP1 cathode ray tube, Figure 35. The phosphor screen first used was prepared by painting a suspension of P4 phosphor in sodium silicate solution onto a square glass plate. The ratio of sodium silicate to phosphor was greater than desirable, resulting in some burning of brown spots on the screen and in reduced light output. Later a new gun was installed and a 2-inch diameter section of its CR tube phosphor screen replaced the original screen. This screen functioned satisfactorily. The last (of three) guns was installed while it was in a helium atmosphere, by means of a glove box, and no air came in contact with the gun excepting a small amount that could not be purged from the glove box. This last gun at first gave very good service and apparently full
Figure 35. Cross Section of Electron Beam Apparatus
cathode emission; it is now stored in a helium atmosphere for further use. The emission decreased a small amount after several days of use until finally the filament voltage had to be stepped up to about 8 volts instead of the normal 6.3. At this final voltage there was still ample emission.

Shutting down at night seems to be one cause of letting in gases (air) that would poison the cathode; when shutting down the vacuum system, helium at 1 lb. gauge pressure was let in after cooling the diffusion pump until the pressure rose to 1 micron (air). The latter precaution was taken to prevent oil vapor from being driven into the vacuum chamber.
Observations

General Description

In an initial series of experiments ordinary commercial hydrogen at 400 or 20 microns was introduced into the gas chamber, and the resultant discharge in the coil and electrode rf excitation was photographed from the geographic south end of the chamber. The coils were operated all at one phase (single-phase), or in conventional three-phase fashion. The electrodes also were operated either single-phase or three-phase. Discharges were also observed using only air, in which relationships between one excited electrode and three, and between one excited coil and three, were noted. All these observations were under low magnetic fields, produced by dc magnet current of 0—30 amperes. Much higher dc magnet currents were then used, with hydrogen, and photographs were taken, as the magnetic field or excitation to the electrodes was changed; cyclotron resonant effects were watched for, but not detected.

Underlying the photographic work is the assumption that light output of a given region in the plasma increases with increasing ionization. When high-energy plasmas are observed, this assumption is incorrect. Use of the assumption is from the belief that there has been as yet no high energy plasma, since no regions have been seen emitting the bright red light of atomic hydrogen plasma; the light has been predominantly the bluish light characteristic of excited molecular hydrogen.
Cyclotron resonance phenomena were looked for in other experiments with hydrogen and deuterium gases, by various techniques, but no definite success in observing such phenomena can be reported.

In order to know more about the fields inside the coil and electrode configuration, an electron beam was sent along the (evacuated) Pyrex vacuum chamber and deflection of the beam was observed on a phosphor screen.

Finally, hydrogen and deuterium plasmas were ionized and observed photographically, using different phasing of coils and electrodes. No pronounced difference was observed between these later plasmas and the ones observed earlier in the same high magnetic fields.

Initial Plasma Observations

Initial observations were mainly to determine the general nature of a three-phase rf gas discharge as compared with a single-phase discharge, the minimum pressure at which the gas could be ionized, and whether any cyclotron resonance could be observed; a minor objective was to determine what effect the dc magnetic field would have on the plasma. All of the plasma photographs were taken from the end illustrated in Figure 13. In all the initial observations, the excitation frequency was 4.15 megacycles/second as determined by the crystal oscillator. The cyclotron resonance dc magnet current for this frequency and for the $H^+$ ion is 965 amperes, which produces 2,700 gauss in the center of the magnetic mirror.
In all the initial plasma observations, Figures 36—146, phasing of the three-phase coils and three-phase electrodes about the gas chamber (Figure 23) was as follows, except as noted:

- Coil 1, 0 degree.
- Coil 2, 120 degrees.
- Coil 3, 240 degrees.
- Electrode 1, 180 degrees.
- Electrode 2, 300 degrees.
- Electrode 3, 420 degrees.

Phasing was accurate to within 5 degrees of these values, and amplitude of rf voltage on the electrodes differed from one electrode to another by less than 10%; rf voltage across the coils differed from one coil to another at most by the same amount.

Figures 36-116 were taken with a Watson camera using a Wollensak lens; this camera was adapted for use of Polaroid film; it was focussed on the center of the gas chamber. Figures 118—146 were taken with a Graphlex reflex camera also adapted for Polaroid film.

In Figure 83 the narrow ring of light is a faint glow from a hydrogen discharge at the walls of the glass bottle. This picture serves to locate the edge of the bottle at the center plane. In viewing all in Figures 36 through 116, one might use a circular mask 1-3/16 inch in diameter, in order to see only light given off directly by the plasma.

Figures 36 through 70 comprise a series of pictures of ionized $H_2$ gas at 400 with various dc magnet currents and combinations of three-phase or single-phase rf operation. Figures 71—103 are with $H_2$ gas and similar conditions excepting that the pressure is 20 microns. Figures 104—110 are with $H_2$ at 400 microns, but the electrode excitation was varied. Table 4 gives a summary of the operating conditions for Figures 36—110.
Figures 36—1*1; three-phase electrodes only; 500 microns Hg; 1000 vdc on 613 amplifiers; electrode and coil geometry as per Figure 26; phases as on page 87; DC magnet current indicated above.

Figures 36—1*7; single-phase electrodes only; some daylight came in from the side; otherwise same as previous. All Figures 36—1*7 on Polaroid type 400 film, f/16 1/2 sec.
Figures 18—59: three-phase coils only; electrodes grounded; 1000 vdc on 833-A's; 100 microns He; 1/50 sec f/11.

All Figures 18—59 on Polaroid type 117 film; phases as per previous figures.

Figures 50—59: single-phase coils only; 1/25 sec f/11; otherwise same as conditions at left.

Figures 18—59. Discharge in Hydrogen at 100 Microns; Three-phase and Single-phase Coils Excited.
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Figures 60–70: same conditions as at left, except reversed dc magnet current, as indicated.

Figures 60–70: Discharge in Hydrogen at 100 Microns; Three-phase Electrodes with Three-phase Coils, Excited
Figures 71–76; three-phase electrodes only; Figures 71–73, on Polaroid type 100 film at 1 sec f/22; 39 and 40 on Polaroid type 17 film at 1/25 sec f/22 and 1/50 sec f/16 respectively, 76 on Polaroid 100 film at 1 sec f/22.

Figures 77–82; single-phase electrodes only; all 1/25 sec f/11.
All Figures 71–82, 20 microns H₂, other conditions as in previous figures.

Figures 83–87; three-phase coils only, electrodes grounded; 1600 vdc on 833-A's; phases as in previous figures; for Figure 83 only, 1/25 sec f/11. All figures except as noted, 83–93, 20 microns H₂, Polaroid type B7 film at 1/100 sec f/11.

Figures 88–93; single-phase coils only, electrodes grounded; 1600 vdc on one 833-A driving all three coils.

Figures 83–91. Hydrogen Discharge at 20 Microns; Three-phase and Single-phase Coils Excited
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<td>95</td>
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<tr>
<td>102</td>
<td>-25</td>
</tr>
<tr>
<td>103</td>
<td>-30</td>
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All Figures 94–103: three-phase coils and three-phase electrodes excited, phasing as per previous figures; Polaroid type 17 film, 1/100 sec f/16; 1000 vdc on 633-A's and on 613-A's; 20 microns H₂. Figures 100–103; reversed dc magnet current as noted above.

Figures 94–103. Discharge in Hydrogen at 20 Microns; Three-phase Coils and Three-phase Electrodes Excited.
Figures 10b—110. Hydrogen Discharge at 400 Microns; Constant Three-phase Coil Excitation, with Varied Three-phase Electrode Excitation, at 0 and 30 Amperes DC Magnet Current.
Figures 111—116. Discharge in Air at 1000 and at 260 Microns; Single and Multiple Electrodes Excited
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<td>400</td>
<td>3 - Ø</td>
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<td>0 to 30</td>
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<tr>
<td>42—47</td>
<td>400</td>
<td>1 - Ø</td>
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<td>48—53</td>
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<td>3 - Ø</td>
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<td>94—99</td>
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<td>100—103</td>
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<td>3 - Ø</td>
<td>0 to -30</td>
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<td>104—110</td>
<td>400</td>
<td>3 - Ø</td>
<td>3 - Ø</td>
<td>0 or 30</td>
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(varied amplitude)
Relevant data are given with the figures. Considerable detail sometimes came into the picture from the ends of the mirror magnetic field region even though the camera was focused on the center. The bright areas at the edges of the bottle in Figures 36—47 were predominantly at the center plane of the bottle, but the bright areas in Figures 60—70 had some longitudinal structure. The bright areas nearest the center of Figure 87 and similar pictures were located at the ends of the mirror field near maximum magnetic field. In those pictures the light came from bands which extended from one end of the mirror field to the other; however, in Figures 71, 77, 88—93, and 94 the brightness seemed to extend all along the bottle and could not be located at any one dense region.

The streaks running through the central portion of the pattern of Figure 41 came in when magnet current reached 30 amperes. (Higher current values were not attainable at the time of taking these pictures.) The streaks appear to represent a discontinuity in charge distribution inside the gas as a function of dc magnet current. Evidence of a similar discontinuity comes in at 33 amperes in Figures 65 and 70.

Figures 104—110 show the effect of increasing electrode voltage when a constant three-phase excitation is applied to the rf coils at 0 or at 30 amperes dc magnet current. Here there is a complicated rotational structure. In Figure 104 the bright bands are at locations of rf coils; in Figures 105 and 106 (with the electrodes more intensely excited) they are at locations of rf electrodes.
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At lower gas densities and low dc magnet currents there was not enough structure to the ionization to warrant pictures.

A few observations were made using air for the discharge instead of hydrogen.

The ionized air gas was observed under various rf power connections to the elements of the rf assembly surrounding the center region of the gas chamber. It was possible to excite any one of the rf elements, or any combination of them. As seen from Figures 111—116, there is a decided change in the distribution of light when the pressure is reduced to 260 microns from 1000 microns. There was some difference in amplitude among the electrode voltages, which caused the difference in size of the three lobes, in Figure 116. At 260 microns the effect of the 120-degree phase relationship between electrodes appears to be an isolation of the ionizing effects of the electrodes. At 1000 microns this isn't true, possibly because at this pressure the electric field does not penetrate enough to cause any phase-correlated interaction between various parts of the gas.

Some of the more interesting facts regarding Figures 36—116 are:

1. At 400 microns, single- and three-phase electrodes produce the same type of ionization structure (Figures 36—47).

2. At 400 microns, and with less than 30 amperes dc, the phasing of the electrodes seems to be of little significance. (Figures 36 and 42.)

3. At 20 microns, phasing of the electrodes is of some significance.
4. There is a counter-clockwise rotation of the three white areas produced in 400 micron H₂ by single- or three-phase electrodes when dc magnet current increases from 0 to 30 amperes (Figures 36—46). (This rotation can be measured, and result of such measurement is reproduced in Figure 117.) No explanation is presented here, although there is a possibility of valid explanation in terms of electron conduction along lines of magnetic flux.

5. No such rotation appears as magnet current is increased when three-phase coils are used rather than electrodes (Figures 48—59).

6. Some rotation of the three light patches occurs when a combination of three-phase coils and three-phase electrodes is used (Figures 61—95).

7. The three bright lines at 400 microns extending to the center of the bottle from the edges, as in Figure 60, are rotated by the magnetic field until, as in Figure 63, they lie along the surface of the glass.

8. At 20 microns a small increase in dc magnetic field enhances ability of the rf coils to ionize the gas (Figures 83—84).

9. At 20 microns there is considerable difference, in structure of the ionization, between three-phase and single-phase coil excitation (Figures 83—93). The difference is that three-phase excitation causes the visible light to be more localized near the edges of the chamber, and it results in a dark center region.
After these observations had been made, higher magnet currents became available, and observations were made with hydrogen using these much higher currents, as shown in Figures 118—146. It was thought that ion cyclotron heating would take place most readily at as low a pressure as it would be possible to operate, hence when the higher magnet currents made it possible to operate at two microns this data was taken. At times lower pressures could be ionized, and this minimum pressure for ionization seemed to depend upon unpredictable conditions of the vacuum system and its history; two microns was picked as a pressure that could reliably be ionized.

At higher dc magnet currents and two microns (hydrogen), there was more structure to the discharge, and there was a trio of small bright areas at the end of the discharge chamber at the position of maximum magnetic field. As voltage was increased from 0 to 1750 volts on the 813's, these areas rotated clockwise, rather than counterclockwise as certain bright areas did in lower magnet current pictures. The effect of increasing magnet current, with given constant excitation to the rf elements, was to make the various parts of the observed pattern sharper, and the bright portions a little brighter. The cyclotron rotation frequency for a proton is 4.15 megacycles, at a magnet current of 965 amperes; there was no significant change in appearance of the discharge at this current. However, there is a noticeably greater brightness in the pattern of Figure 144 at 975 amperes. This could be caused by difference in the film or exposure. No difference was noticeable to the eye. Barring such experimental errors one might
attribute this increase at 975 amperes to a cyclotron resonance absorption of rf energy by the gas. This matter should be examined further. Cyclotron resonance is covered in the following section.

Cyclotron Resonance Observations

It would be desirable to produce and detect the ion cyclotron resonance effect. Other observers\textsuperscript{10} have detected it in higher-powered plasma devices; the Omegatron\textsuperscript{11}, a low-powered device employed in gas analysis, is based on the cyclotron resonance principle.

It had been observed in all the gas discharges that the color was bluish, and that in spectroscopic analyses of the discharge the hydrogen molecule spectrum predominated. (However, in preliminary work at the Physics building with single-phase coils, the rf ring discharge described by Series\textsuperscript{12}, producing a very bright red atomic hydrogen gas, was formed in a one-liter flask.)

Early efforts to detect any resonance effects in hydrogen by looking at the hydrogen Balmer lines while varying the dc magnetic field proved fruitless.

There is not enough power from the rf system to produce the atomic state of the gas in the abundance typical of the atomic gas in, for example, a Wood's discharge tube. One reason for this is that the strongest field produced by the coils lies inside the coil loops, whereas, the geometry used in these experiments require the gas to be in the (weaker) external part of the coil field. Another possible reason is that ions were not contained in the central region long
enough to be sufficiently heated for the molecule to be broken up. Still another limitation may be that although application of the magnetic field may help containment, at the same time more intense cross-fields of excitation are required to heat the gas.

On October 5, 1961 the rf frequency was changed from 4.15 to 1.86 megacycles, which would give a cyclotron resonance to the deuteron or to the hydrogen molecule ion at 860 amperes dc magnet current, or 2,400 gauss. It was thought that some dc magnetization-dependent effects might be observed with one or another of these gases, even though the glass bottle is not of large enough diameter to allow energy of over 2 kev for a deuteron in a 2,400 gauss magnetic field.

A pair of GM counters were mounted at the north end and near the center of the gas chamber with the end-windows next to the quartz end window and the glass bottle respectively.

Ordinary commercial hydrogen or deuterium (General Dynamics purity 99.5%) were the ionized gases.

It was possible to maintain an ionization in deuterium in pressure as low as 0.5 microns. There was no appreciable count rate in the GM counters at this pressure, at any magnet current. With a pressure of 8 microns, however, there was an appreciable number of counts above background, and by inserting absorbers over the GM counters it was found that the counts were from ultraviolet radiation. A broad increase in counts/minute, having its highest value at about 1000 amperes, was noted.
With hydrogen gas the same was found to be true—counts in the GM counters were from ultraviolet radiation, and a broad maximum count rate was found at 1000 amperes. The count rate for this gas was measured and is given in Figure 147, with a sketch of the geometry.

Air was found to emit the same type of radiations, but no measurement of counts/minute as a function of dc magnet amperes was taken.

Electron Beam RF Field Probe

After the previous plasma experiments had been done, there was still some doubt that the phasing and rf fields inside the rf load assembly were what was to be theoretically expected. The main purpose in all pictures involving the electron beam was to ascertain whether there is a revolving field of force inside the rf coil assembly and another inside the electrode assembly, and whether these fields can be phased in such a way as to completely balance. (If such were true, amplitude of the electrode field could be increased above the amplitude of the induced electric field of the coils, keeping the same phase adjustment, so that positive particles undergoing cyclotron acceleration in a gas discharge might drift toward center as discussed in Chapter I.)

Electrical probes were considered as a means of measuring the rf fields, and some probes actually were constructed. One probe consisted of three very small coils which could be rotated about the gas chamber axis in the three-phase assembly, and any one of which could
Figure 117. GM Count Rates from Hydrogen Ionized Gas as a Function of DC Containing Magnet Current.
be connected to the oscilloscope through a twisted-pair lead. A simple tuned circuit, connected across the oscilloscope input, was adjusted to give maximum voltage at the operating frequency. This probe functioned very well in the field of an rf coil, but, as would be anticipated, it did not give any response to electrostatic fields. Another probe consisted of a small capacitor attached to a coaxial cable leading also to a tuned circuit, which was adjusted to give maximum voltage on the oscilloscope at the operating frequency. This probe functioned very well in the field of a capacitor, but gave no indication when inserted into the interior of a rf coil. These results were found to be in accordance with ordinary electrical theory.

Thus, it was necessary to devise a charged-particle apparatus for indicating the total accelerating force on a charged particle within the three-phase assembly of coils and electrodes. A cathode ray (CR) tube was first employed, to explore its possibilities. Subsequently, the electron beam apparatus previously described (Figure 35) was constructed and used to obtain information about the fields; the electrode phasing was modified on the basis of this information. A chronological description of these observations follows.

Figure 148 shows a cathode ray tube 1EPl lying inside a three-inch Pyrex pipe on which was would an rf tank coil; the coil was energized by 1.86 mc rf current. When the cathode ray tube was rotated about the axis of the pipe, the electron beam deflection seen on the face of the CR tube rotated through the same angle. The
Figure 14.8. Deflection of Beam of Type 1EPL

CR Tube in RF Coil
deflection was always tangential to the coil. This deflection was caused by the induced electric field inside a coil, such as that in a Betatron accelerator. This experiment shows that the \( e \times B \) force on the electron beam in the magnetic field of the coil is negligible at this operating frequency. (If the frequency were to be steadily decreased, with constant rms coil current maintained, eventually a frequency would be reached at which the \( e \times B \) force would predominate over the induced force associated with \( \frac{dI}{dt} \).)

One may conclude from this experiment that electron beams can be used to indicate the instantaneous induced force on electrons inside the coil at 1.86 mc and above. (At normal electron gun accelerating voltages the time of flight of an electron is very much less than the period of applied alternating current in the rf coil.)

On November 14, 1961, this same CR tube was mounted inside the three-inch Pyrex gas chamber, supported by two lucite disks which were attached to an off-center \( \frac{1}{2} \)-inch dowel rod. Pictures of the CR trace were taken from the usual geographic south end of the gas chamber; see Figures 149—157. In Figure 149 the CR tube is in the center of the chamber; the centermost and smallest circle is the electron beam trace, the next \( \frac{1}{2} \)-inch circle is the CR outside diameter, and the circle at 8 o'clock is the wooden dowel end. A rubber band held the CR tube in place; this band is seen as a belt around the CR tube and the wooden dowel.

Figures 149—151 show that the shape of the trace was not influenced by any asymmetry of the electron gun, or other metallic objects,