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DESCRIPTION OF SPACE SIMULATION EXPERIMENTS UTILIZING PLASMA PRODUCED BY CONTACT IONIZATION

by
R. G. Quinn

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ERRATA

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TABLE OF CONTENTS

ABSTRACT

A number of experiments utilizing thermally ionized plasmas for laboratory simulation of terrestrial plasma phenomena are discussed.

It is shown that most of the essential features of the dynamics of charged particles trapped in the earth's field can be simulated in the laboratory. Further, it is possible to systematically and in a controlled manner violate the various adiabatic invariants of the motion by causing perturbations through electric and magnetic fields and collisions.

It is also shown that the conditions important for wave phenomena in the earth plasma can be simulated in the laboratory. The size of the experimental apparatus will vary with the particular phenomena one wishes to simulate but even in the largest case is still experimentally feasible.

A few clarifying remarks concerning the proper relation of laboratory simulation experiments with theoretical and experimental space research are also made.

INTRODUCTION

A series of laboratory plasma simulation experiments will be described which offer a high degree of flexibility, in controlling significant parameters, in the use of diagnostic techniques, and in simulating a very broad range of geophysical phenomena. Before discussing these experiments it is appropriate and instructive to consider the relation between laboratory simulation experiments and theoretical and experimental space research. The proper function of laboratory simulation experiments is not to replace experimental space research but to enhance the progressive interaction between space experiments and theory.

Experiments in the space environment are impeded by the degree of accessibility, fluctuations, instabilities and lack of control of the medium. Further, they are costly and limited to measuring only a few selected parameters over short time or space intervals. This lack of information impedes the progress of theoretical developments causing the overall effort to progress at a reduced rate. Simulation experiments can enhance the interaction on the theoretical side by suggesting the general classes of phenomena which are likely to occur and the relative importance of various physical processes which must be considered in any full scale theory. On the experimental side progress can be enhanced by determining the validity and applicability of various experimental techniques used in space probes.

Unfortunately the performance of this function has been rather spasmodic and limited probably for two reasons. One, which has been largely eliminated, was the rather slow development of plasma technology prior to the search for controlled nuclear fusion. The second which still exists is a general misunderstanding of how one successfully simulates a given plasma phenomena on a different scale. This misunderstanding rests in the so-called "laws of similitude" (Cobine). These rather dubious "laws" are based on an experimental observation (called Paschen's law) that the sparking potential of a gas discharge will not change with pressure if appropriate changes in the dimensions of the device are made. This observation together with a number of simplifying assumptions in the analysis of the properties of a linear discharge tube leads to a set of transformation factors for various physical quantities. These transformation factors are valid for the linear discharge. They also indicate that a total simulation of the terrestrial plasma field environment is impossible. The basic misunderstanding lies in the fact that, for every physical process, there are certain parameters which are critical and others which can largely be ignored, so that one can retain the essential identity of a given process by scaling only the important parameters.

If we are to realize the full potential of laboratory simulation experiments in enhancing space reseach, we must adopt the position that each geophysical phenomena can be separately analyzed with respect to essential characteristic features and the parameters which govern them to determine if these can be scaled in a preservative manner. Further, because of the lack of knowledge of the magnitude and variation of many space parameters, simulation experiments which at first glance seem inapplicable should be examined for effects and phenomena which may be relevant to full scale theory and full scale experiments.

EXPERIMENTAL BACKGROUND

The quest for controlled nuclear fusion has provided a most important impetus to the development of plasma technology. Of particular interest to this discussion is the development of the Q device (Rynn and D'Angelo). This device provides essentially a stable, fully ionized, low temperature plasma trapped in a cylindrical magnetic field bounded at the ends by two hot conducting surfaces. It has been used in numerous experimental investigations concerning fundamental plasma properties. One of the unique features of the device is the method of generating the plasma. This method of generation is similar to that suggested for the experiments described herein.

(Langmuir and Kingdon) discovered the principle that a hot metal surface will singly ionize the atoms of a gas which comes in contact with it, if the ionization potential of the gas is less than the work function of the metal. There have been a large number of experiments performed utilizing this principle with such vapors as potassium, sodium, cesium and barium on metals such as tungsten, tantulum and rhenium. The configurations of the generating systems are varied but may be generally classified as vapor pressure devices, atomic beam devices, or diffusion devices (Hernquist et. al. and Forrester). For the purposes of our discussion we will consider the case of cesium on tungsten since this is the most common combination. In the vapor pressure device, one utilizes a hot tungsten surface in a cesium atmosphere. The degree of ionization will be determined by the temperature and area of the surface, and the cesium pressure. The temperature of the plasma will be essentially that of the tungsten surface. The general trend of such devices is that for a high degree of ionization one must use small volume devices to minimize recombination losses. The atomic beam device utilizes a reacting oven in which a mixture of cesium chloride and calcium is heated to approximately $400^{\circ}C$. The calcium replaces the cesium which escapes through collimating tubes aimed at a hot tungsten surface. The temperature of the oven provides a good control of the flow of atomic cesium and hence the plasma density and degree of ionization. For example fully ionized cesium plasmas having a density of 10^{12}/cc and a temperature of $2500^{\circ}K$ have been obtained. The pumping speed also provides a method of controlling the plasma indirectly. The diffusion device in general relies on the fact that atomic cesium diffusing through a hot porous tungsten element will emerge at the surface in an ionized state. The percent ionization and the density can be controlled in a number of ways including electrical biasing and electron enrichment.

The particular method or combination of methods used has been designed to suit the needs of the experimenter. In general one can obtain plasmas with densities ranging from 10^6 to 10^{12} per cc, temperatures from 2000 to $3000^{\circ}K$, and degrees of ionization from 40 to 99%. Plasmas of this type are amenable to many diagnostic techniques such as electric and magnetic probes, microwave scattering, transmission and absorption, noise emission and in the case of barium, visible spectroscopy.

With these general features as background we now wish to examine a number of simulation experiments.

SIMULATING PLASMA DYNAMICS IN A DIPOLAR MAGNETIC FIELD

One of the most important geophysical plasma problems is the motion of a plasma trapped in a dipolar magnetic field. The best understood aspect of this motion is that associated with trapped single particle motion with no external perturbations. A most useful approximation based on a general adiabatic invariance theorem of classical mechanics gives a clear physical picture of this motion. In this approximation the motion is viewed as the superposition of three cyclic motions; a gyration about a field line, an oscillation or mirroring between two latitudes, and a cyclic drift in the longitudinal direction. The conditions for the validity of the theory can be stated in various ways, (Alfven) perhaps the simplest of which is that, for a static dipole magnetic field and no electric field,

$$\rho / r \ll 1 \tag{1}$$

where

ρ is the radius of gyration of the charged species

r is the distance from the guiding center to the center of the dipole

Now the effects of perturbations of this steady state which may be generally classified as collisions, spatial and temporal variations in density, electric and magnetic field are of course important since these are the normal occurrences in the geophysical environment. These are basic areas of space research both theoretical and experimental. It would therefore be quite useful to develop a simulation experiment which establishes a trapped plasma satisfying the conditions of the approximate theory and can be subjected to the kinds of perturbations which exist in the terrestrial environment in a systematic and controlled manner which can be effectively diagnosed. Such an experiment will now be described.

Steady State Investigations

In attempting the simulation by ascertaining the important features, the first consideration to recognize is that the adiabatic theory is a single particle theory. For a real plasma this means that the time between collisions of any kind must be long compared with the characteristic times of the motion, namely the gyro time, the mirror time and the drift time. Next, one must have a static dipole magnetic field and a plasma such that condition (1) is satisfied.

Consider now a permanently magnetized sphere having a dipole moment of 10^4 gauss cm^3 and a radius of 20 cm. Such a sphere can be easily made of ceramics or nickel alloys and provides the static dipole field. This sphere is placed in a vacuum vessel which is evacuated to a pressure sufficient to eliminate the effects of all residual gas, say 10^{-8} torr. A plasma is then generated by contact ionization within the dipole field. The properties of such a plasma are shown in Table 1. It can be seen from the values of the critical parameters that the plasma satisfies the conditions that the shortest collision time, the electron-ion, can be made as much as two orders of magnitude longer than the longest cyclic time. Further, the condition $\rho/r \ll 1$ is satisfied even in the case of choosing a massive ion such as cesium and assuming all of the kinetic energy to be perpendicular to the magnetic field.

The steady state density distribution would be governed by the nature, position and geometry of the ionizing source as well as the mode of generation. A large range of flexibility in this matter is available to the experimenter. For example, point, line, or surface sources could be utilized. Because of this broad range we will consider a simple case to demonstrate the flexibility of the experiment and give a qualitative picture of the conditions.

Consider the ionizing source to be two hot tungsten wires in the equatorial plane around the surface of the sphere operating in the vapor pressure mode. The dc heating currents could be made to flow in opposite directions in two closely spaced wires to eliminate the effects of their magnetic fields. Such a situation would allow one to vary the degree of ionization and the density by changing the temperature and size of the wire or the pumping speed. To obtain a highly ionized plasma one could replace the wires with hollow perforated tubing through which atomic cesium could flow and emerge in an ionized form. Here the density could be varied by changing the flux of the neutrals from the reactive oven.

The approximate extent of the trapped plasma belt can be computed roughly by considering radial diffusion and recombination processes. Let us make the further simplifying assumptions that the density has an average value of 10^8 per cc and the magnetic field has an average value of 100 gauss.

We first compute the average time it takes an electron-ion pair to recombine, t_s.

$$t_s = \frac{1}{\alpha N}$$

where α is the recombination coefficient and will be assumed to be 10^{-10} cm^3/sec and N is the density. This value of α is subject to some dispute in the literature. We have chosen the most extreme value (Mohler) to make the extent of the plasma smallest. The corresponding recombination time is 100 seconds.

We next consider how far a particle will diffuse outward from the sphere in 100 seconds, in the radial direction in the equatorial plane in a reference frame rotating with the longitudinal drift velocity. The mean squared distance $\langle\Delta x\rangle^2$ traveled by an average particle in a random walk is

$$\langle\Delta x\rangle^2 = Na^2$$

where

N = the number of steps

a = the length of the step

One can show that the maximum step due to an electron-ion collision is one electron gyro radius. We assume classical ambipolar diffusion which is always of the order of the slower moving species. In the case of cross field diffusion the associated step is the electron gyro radius. Further we assume a fully ionized plasma so that the collisions of importance are electron-ion collisions. The results of this calculation shows that the plasma will diffuse at least 30 cm before recombining. Thus a trapped belt extending 30 cm from the surface of the sphere in the equatorial plane would probably represent the smallest case. Other generation geometries would of course have larger associated belts. The purpose of the above calculation is to demonstrate that, even under the worst conditions, one would have quite good spatial resolution in the application of Langmuir probes, that the size of the vacuum vessel needed is not large, and that the shape of the distribution will depend in general on the magnetic field, the geometry of the generator, and the nature of the vacuum system, all of which can be controlled.

Perturbation Investigations

The effects of collisions can be analyzed by varying the degree of ionization and the plasma density in such a manner as to independently and successively violate the adiabatic conditions for each cyclic motion. Temporal and spatial variations in density can be studied using pulsed or even periodically varying plasma sources placed anywhere in the field. Pulsed and periodic electric and magnetic field effects can be investigated by appropriate configurations of electrodes or coils. Such studies would provide information concerning possible plasma waves and instabilities.

An image dipole could be used to create neutral points to study the dynamics of the plasma under these conditions. Further, the interaction of a plasma stream with the steady-state configuration could be measured. The variations are thus quite numerous and offer the possibility of simulating a large number and variety of geophysical phenomena for detailed experimental investigation.

SIMULATING WAVE PHENOMENA

We now direct our attention to some of the basic properties of the terrestrial plasma which are important to wave propagation. A table of typical values for the relevant parameters is given in Table II (Al'Pert). These are only average values and do not represent unstable situations. They indicate it is generally true that the magnetic energy density is larger than the kinetic energy of charged particles. Thus the Alfven velocity is less than the electron or ion thermal velocity. Further the plasma may be classified almost universally as a cold or quasi cold plasma and that the electron and ion temperature are approximately equal. Thus the earth plasma is rich in low frequency waves and oscillations. They generally include transverse electronic, hydromagnetic, and ion cylcotron waves as well as longitudinal waves of hybrid frequencies depending on the plasma and gyro frequencies. If the plasma is non-isothermal a whole new variety of waves is possible.

Whether certain kinds of waves will exist or propagate in a plasma depends on excitation and damping mechanisms and many properties of the plasma and fields. To simplify the analysis of the problem one usually appeals to a set of characteristic times which can completely characterize the plasma. For example, the basic relaxation times characterizing electromagnetic field-plasma interactions are:

1. Electromagnetic Wave period
2. Plasma period
3. Gyro period
4. Momentum relaxation time
5. Maxwellianization time

6. Energy relaxation time
7. Total density change relaxation time
8. Characteristic diffusion time
9. Electron density increase time
10. Exposure time (finite)

In general, the physical process associated with a particular relaxation time becomes important when this relaxation time becomes smaller than the relaxation times of other competing processes. Also a physical process becomes negligible when its relaxation time approaches infinity. Times 4, 5, 6, are considered when the coupling of electromagnetic fields to the plasma through interparticle collisions is important. Times 7 and 8 must be considered when electric field intensities are sufficient to change the width or shape of the electron distribution function. Time 9 must be considered if ionization by collision or attachment is important. Time 10 which is finite is usually included when a high power disturbance is present. Times 1, 2 and 3 are usually the most fundamental times characterizing the plasma. The plasma and gyro periods refer to either electrons or ions depending on the nature of the signal frequency.

The Clemmow-Mullay-Allis diagram shown in Figure 1 is an example of how one characterizes plasma properties using these basic times. It presents a systematic way of classifying electromagnetic wave propagation characteristics in a collisionless, low temperature plasma at low power levels. From Table II it can be seen that it is generally true that the terrestrial plasma is characterized in the shaded area of the diagram. Thus, for purposes of simulating this environment, the laboratory plasma must be characterized in this same region.

The final and experimentally the most difficult point is the fact that the terrestrial plasma is essentially an unbounded medium. Practically this means, with respect to electromagnetic wave propagation, that the laboratory plasma must be such that its physical extent is large compared with the wavelength or arranged so that the effect of the boundaries are negligible.

We will now describe an apparatus which will establish various conditions of interest for simulating terrestrial phenomena.

Experimental Apparatus

A schematic diagram of the proposed experiment is shown in Figure 2. The conducting coils should be capable of generating a homogeneous magnetic field up to 300 gauss and a mirror geometry between the end plates if desired. An appropriate source of alkali atoms is delivered to the hot end plates. This source could be either a vapor pressure mode or a porous plug device. The end plates are housed in a vacuum system whose walls are cooled cryogenically or, if sufficient, using conventional refrigeration techniques.

The diameter and length of the plasma would be set by the type of simulation experiment desired. Electromagnetic wave propagation experiments concerning reflection, transmission, Faraday rotation and whistlers would set the requirement that the size of the plasma be large compared with the wavelength. We will adopt a diameter of 10 meters to fulfill this condition realizing that smaller versions might be applicable for other phenomena and that this size probably represents an upper limit from the standpoint of vacuum technology and the problems associated with generating the magnetic field.

In considering the thermal problems, we have noted that the nature of the source could take the form of a matrix of porous plugs, discs, etc. However, we chose the limiting case of a solid surface heated to 2500^{o}K. The power radiated by a black body at this temperature is approximately 200 watts per square cm. This would correspond to a total radiation for both surfaces for the largest device of approximately 300 megawatts. This amount of power is well within acceptable limits. (The cost of such a power plant would be small compared to average space experiments.) It should also be noted that due to the lower emmissivity and the fact that all of the surface need not be heated that one could expect to cut the power requirements by at least an order of magnitude. Finally, the use of heat shields and cooling would protect the vacuum vessel walls.

Plasma Properties

The properties of the plasma are essentially those of a normal Q device with the exception that the densities are less and the plasma is not as highly magnetized to conform with the properties of the terrestrial plasma. We will thus discuss the gross features of the device in terms analogous to those originally presented by (Rynn) because of their simplicity. There have of course been many improvements in both the theory and experiment since the device was originally proposed but none of the features important for our discussion have been essentially changed.

The analysis begins by considering two hot end plates separated by a distance L. Azimuthial and radial variations in the end plates are neglected and the continuity and momentum equations are applied to derive the operating conditions. Simplifying assumptions consistent with experimental conditions and a requirement that the plasma density vary less than one percent along L lead to a condition for the maximum length of the device. This length is shown to vary directly with the plasma density, having a value of approximately one meter at a density of 10^{12}/cc. Consequently, this limit provides essentially no restrictions on the length of the proposed device when operating at the much lower densities proposed.

The next question of importance would be the variation of density in the radial direction. Calculations and experiment show that if the entire end plate is a hot surface, essentially a uniform plasma density can be obtained. Further, uniform densities of a lower value could be obtained by heating only portions of this area or equivalently utilizing a matrix of porous plugs. The results suggest that one would only need to utilize half the area making the heating problem much less severe.

Given these considerations we conclude that it is experimentally possible to generate a plasma having the properties shown in Table II.

Thus we see that

$$\omega_p > \omega_H > \Omega_p > \Omega_H$$

for both the terrestrial and laboratory plasmas. In addition the condition

$$\Omega_H < \nu_{ei} < \Omega_p \qquad \text{when } h < 1000 \text{ km}$$

$$\nu_{ei} < \Omega_H \qquad \text{when } h > 1000 \text{ km}$$

can be simulated by lowering the plasma density.

Many other variations are also possible such as, causing the plasma to stream along the axis by operating one end plate cold;

creating density gradients along the axis; lowering the ion temperature with respect to the electron temperature; and creating a mirror geometry.

With such a device it would be possible to study the broad class of phenomena classified as electromagnetic wave-plasma interaction, such as reflection, transmission, attenuation, faraday rotation, Luxemborg effect, and whistlers. It would also be possible to study phenomena related to non-thermal noise emissions observed in the terrestrial plasma (Bauer and Stone) such as excitation and plasma-electromagnetic wave coupling mechanisms. Finally the characteristics of diagnostic techniques used in space probes can be ascertained. In short, such devices would add significantly to our understanding, interpretation of data, and use of diagnostic techniques both land based and in space, and enhance our understanding of space wave phenomena through controlled laboratory experiments.

CONCLUSIONS

Two types of possible simulation experiments based on generation of plasmas by contact ionization have been discussed.

Emphasis is placed in both cases in scaling the parameters of critical importance to the processes under study. Both are experimentally feasible and offer excellent possibilities in gaining insight into a broad class of geophysical plasma phenomena.

A final, and perhaps most important, motive of this work is to focus on the importance and usefulness of laboratory experiments in providing a firm experimental basis for the sweeping generalizations and simplifying assumptions necessarily made in theoretical space research and for the interpretation of data from commonly used space diagnostic techniques both ground based and in situ.

TABLE I

Magnitudes of Characteristic Values of a Cesium Plasma in a Dipole Magnetic Field

Ion Mass	133 AMU
Neutral Pressure	10^{-8} torr
Diameter of Sphere	20 cm
Dipole Moment	10^{4} gauss-cm^{3}
Electron Temperature = Ion Temperature	2500° K

Characteristic Lengths - Centimeters

Debye Length ($n_e = 10^8$/cc)	10^{-2}
Gyro Radius*	
Electrons	10^{-2}
Ions	1
Distance from Dipole	25

*Calculated assuming all kinetic energy perpendicular to the magnetic field.

TABLE I
(continued)

Characteristic Times - Seconds

	Gyro*	Mirror**	Drift***
Electrons	10^{-9}	10^{-6}	10^{-4}
Ions	10^{-4}	10^{-4}	10^{-4}

Collision Times		$n = 10^8/cc$	$n = 10^6/cc$
Electron - Ion		10^{-4}	10^{-2}
Self, electron		10^{-4}	10^{-2}
Self, ion		10^{-2}	1
Electron - Neutral	1		
Ion - Neutral	10		

** Calculated assuming an equatorial distance of 20 cm and zero pitch angle.

*** Calculated for the equatorial plane and ninety degree pitch angle.

TABLE II

	Height KM	H_o Gauss	N cm^{-3}	$T_e \approx T_I$ °K	$\frac{H_o^2}{8\pi}$	NKT
EARTH PLASMA	300	-1	6	3	-3	-7
	500	-1	5	3	-3	-8
	1000	-1	4	3	-3	-8
	2000	-1	4	3	-3	-9
	$2R_o$	-2	3	4	-6	-9
	$7R_o$	-3	1	5	-7	-10
CESIUM PLASMA		1 - 2	10 - 11	3	1	-3

	Height KM	ω_p	ω_H	Ω_p	Ω_H	ν_{ei}
EARTH PLASMA	300	7	6	5	2	3
	500	7	6	5	2	2
	1000	7	6	5	2	1
	2000	6	6	5	3	1
	$2R_o$	6	5	4	2	-3
	$7R_o$	5	4	3	1	-4
CESIUM PLASMA		10	8	7	4	6

Relevant Earth and Cesium Plasma Parameters

Values are given in powers of 10.

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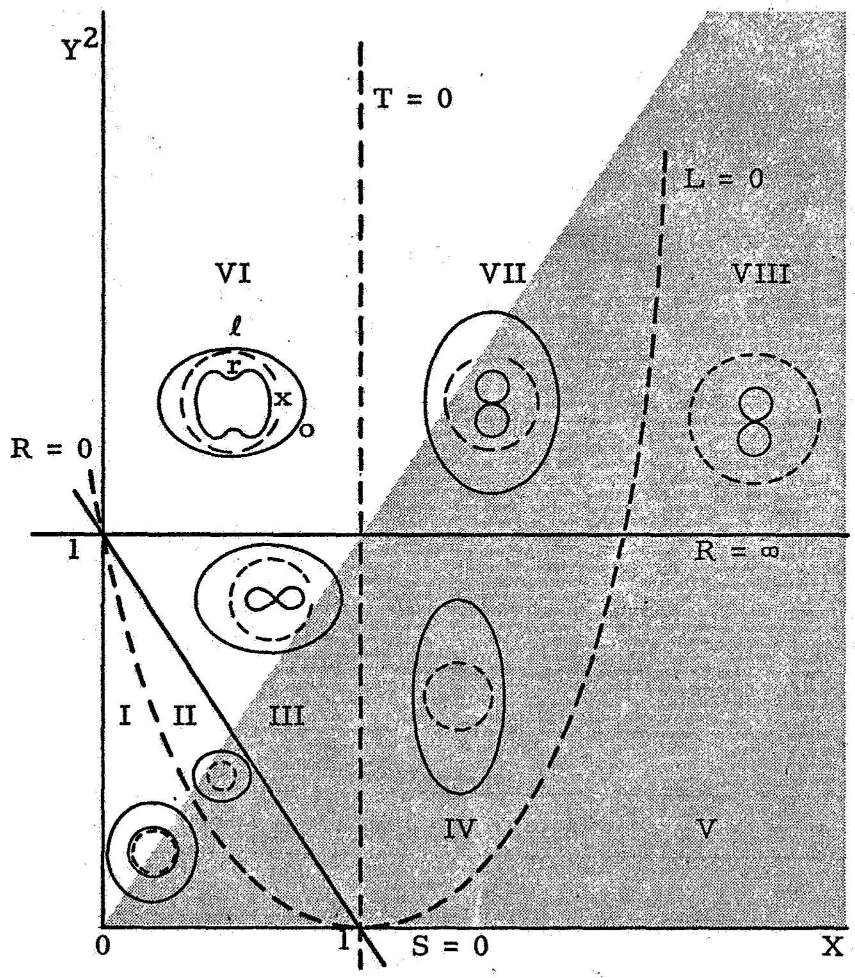

Figure 1. A Clemmow-Mullaly-Allis Diagram. Shaded region corresponds to typical magnetospheric conditions.

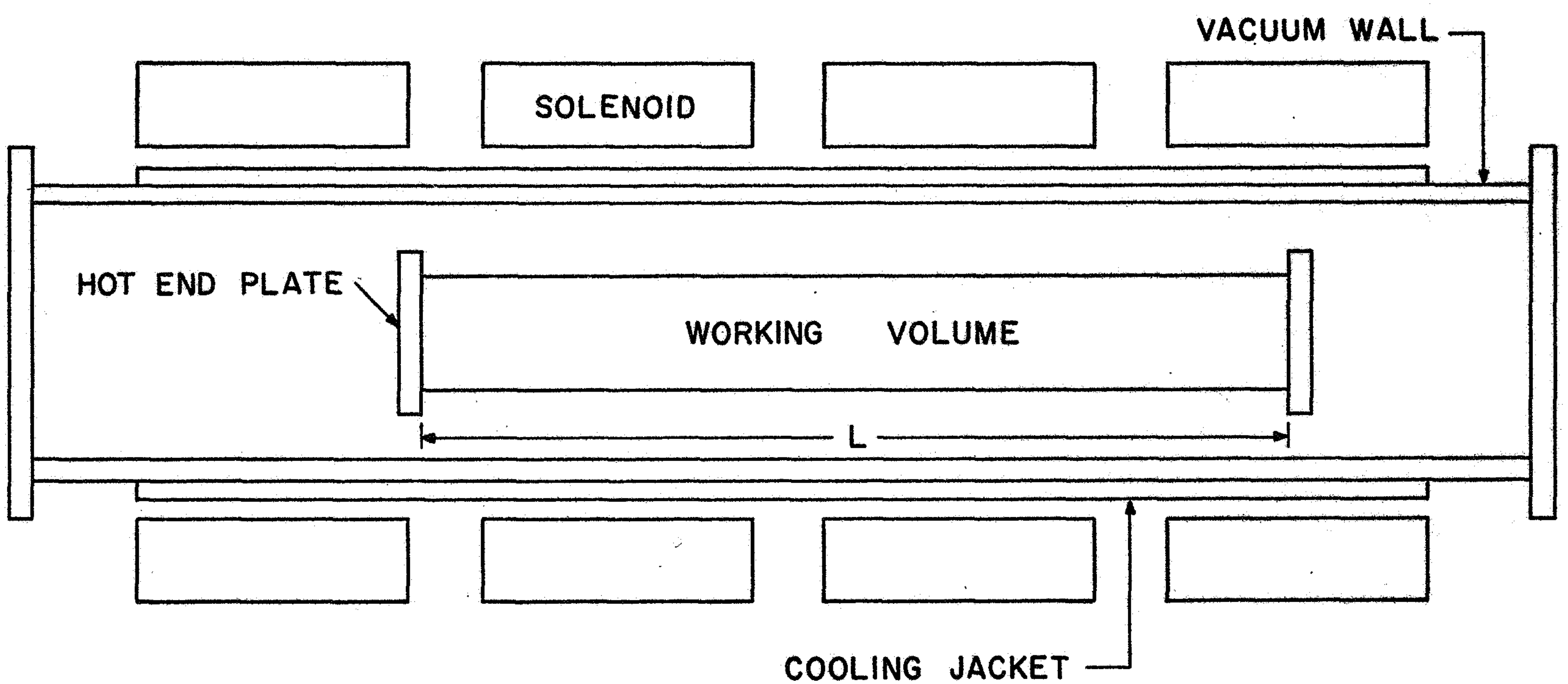

Figure 2. Schematic of Q Machine with Source of Neutrals Omitted