4915-14-Q

RADC-TDR-63-509

4915-14-Q = RL-2117

MICROWAVE-PLASMA COMPONENTS STUDY

TECHNICAL DOCUMENTARY REPORT NO. RADC-TDR-63-509

December 1963

Techniques Branch
Rome Air Development Center
Research and Technology Division
Air Force Systems Command
Griffiss Air Force Base, New York

Project No.5573, Task No.557301

(Prepared under Contract No. AF30(602)-2605 by Andrejs Olte and E.K. Miller, The University of Michigan, College of Engineering, Department of Electrical Engineering, Radiation Laboratory)

Suggested Keywords: Plasma Physics, Microwave Components

ABSTRACT

An equivalent microwave circuit is proposed to exhibit the main features of the electron cyclotron resonance interaction in a waveguide. The essential part of the circuit consists of a non-reciprocal transmission line and similarly coupled resonant circuit. The experimental effort on the plasma package is discussed and some of the experimental difficulties reviewed.

PUBLICATION REVIEW

This report has been reviewed and is approved. For further technical information on this project, contact EMATE, Mr. Joseph M. Schenna, X4251

Approved: Joseph M Schenna
JOSEPH M. SCHENNA
Project Engineer
Electron Devices Section
Techniques Branch

Approved:
for Lt Col USAF
ARTHUR J. FROHLICH, Chief
Techniques Branch
Surveillance and Control Division

TABLE OF CONTENTS

LIST OF FIGURES

INTRODUCTION

This Quarterly Status Report presents work done on Air Force Contract AF 30(602)-2605 for the period 1 July to 30 September 1963[+]. Section I proposes an equivalent circuit for the electron cyclotron resonance isolator . Section II presents the experimental work. Section III gives the conclusions, and Section IV discusses future work.

I THEORETICAL DERIVATION OF ABSORPTION IN THE ELECTRON CYCLOTRON RESONANCE ISOLATOR

This is a continuation of previous work (Quarterly Status Report 4915-13-Q) in which we have developed a first order theory for the non-reciprocal absorption of the TM_{11} mode in a square waveguide that has a relatively thin transverse plasma slab parallel to the waveguide wall and spaced about one quarter distance of the guide width from it. The primary approximation in the theory is the neglect of the electrical effect of the glass container of the plasma on the wave propagation, and the further assumption that the fields in the plasma have the same transverse variation as the TM_{11} mode fields in the empty guide. These approximations are not severe because the absorption is expected to exhibit a stationary character with respect to a variation in the fields. The non-reciprocal behavior of the device results from two facts:

[+] NOTE: Although this is called Quarterly Status Report No. 14, it should be noted that it covers work done in the second quarter of the second year. The first 12 reports were monthly.

1) $\epsilon_{lk}(\bar{H}_0) = \epsilon_{kl}(-\bar{H}_0)$, where $\bar{H}_0$ is the magnetostatic field, and

2) the magneto-ionic plasma slab is placed in an asymmetric position with respect to the magnetic fields of the TM_{11} mode.

An implicit assumption in the theory is that only the TM_{11} mode may propagate. But in our case we have a multimode waveguide; the lower order modes TE_{10} and TE_{01} may propagate as well. However, in the circuit for which we are using the solution we have only a section of the square waveguide which contains the magneto-ionic package. On both ends of this section are the TEM-TM_{11} mode transducers, as shown in Figure 1. In the same figure we have also presented an equivalent microwave circuit which represents the main features of interaction of the waves with this structure. Starting from the left hand side of the circuit we have elements as discussed below. The TEM mode of the co-axial line is represented by an ideal transmission line of characteristic impedance, Z_0 and the propagation constant $j\beta_0$. Both constants are real. If the reference planes are selected properly any loss-free four-port network may be replaced by an ideal transformer. We have chosen to so present the TEM to TM_{11} mode transducer. The section of the square waveguide between the mode transducer and the magneto-ionic package is represented by ideal transmission line of characteristic impedance Z_1 and phase constant $j\beta_1$, both again real. This representation is with respect to the TM_{11} mode. The section of the square guide containing the

Electron Cyclotron Resonance Isolator and its Equivalent Circuit.

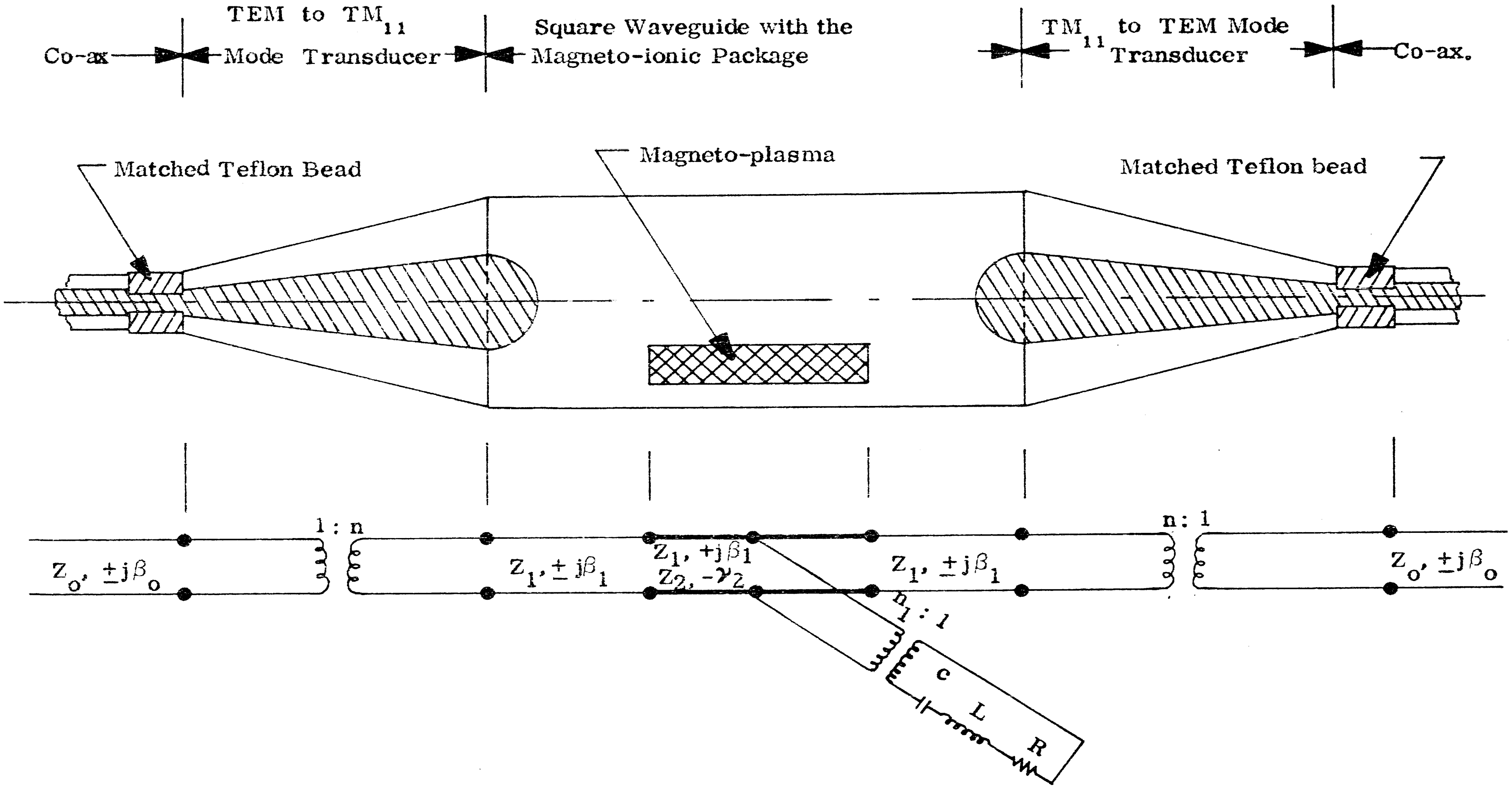


Figure 1

magneto-ionic package is represented again with respect to the TM_{11} mode by a non-reciprocal transmission line. When the propagation is from left to right, both the characteristic impedance, Z_2, and propagation constant γ_2, are complex and the wave suffers attenuation. For propagation from right to left however, the magneto-ionic package is invisible to the wave, and hence the transmission line parameters are the same as for the empty square guide. If the magnetostatic field was reversed, then the non-reciprocal transmission line would also reverse. Since the structure is symmetric with respect to a transverse plane passing through the center of the plasma package, the equivalent microwave circuit to the right of the plasma package consists of an ideal transformer connecting two loss-free transmission lines. This is the same type of circuit as to the left of the magneto-ionic package which already has been discussed. One really should include a coupling network on the ends of the non-reciprocal transmission line. In a general case the network should be a "T" network. However, in some more elementary, but similar situations where the problem has been worked out[+], the effect of this network on the wave propagation is of practically insignificant importance. Therefore, in our case it is reasonable to neglect it as well.

[+] Collin, Robert E., Field Theory of Guided Waves, McGraw-Hill Book Company, Inc., New York, pp 244-247 (1960).

This would be the end of the story of the equivalent microwave circuit of the device if the square waveguide were a single mode guide. On the contrary, it may also propagate the TE_{10} and TE_{01} modes in addition to the TM_{11} mode. However, these modes are axially asymmetric and therefore the TM_{11} to TEM mode transducer will not convert them into a TEM mode. But this is the only mode which is allowed to propagate on the co-axial line. Thus we have a situation in which the mode transducers form shorts on both ends of the square waveguide section as far as the TE_{01} and TE_{10} modes are concerned. In effect, we have a cavity in which may exist TE_{01n} and TE_{10n} resonant modes; n in our case being an appropriate integer. These modes may exist only for certain microwave frequencies. At these resonant frequencies the resonant modes will be coupled by the plasma package to the TM_{11} mode. That means that energy will be taken from the travelling mode and dissipated primarily in the wall losses of the resonant mode fields. The coupling will occur only for the direction of travel in which the plasma section of the guide appears lossy to the TM_{11} mode.

To take into account the power loss out of the TM_{11} mode due to these coupled cavity resonances we have included a series resonant circuit which is coupled by an ideal transformer to the center of the lossy transmission line. It is doubtful that this part of the circuit may be justified rigorously, but the inclusion of the present model appears not only reasonable, but also necessary. Because the cavity walls and the plasma package itself dissipate energy out of the resonant cavity mode we have included a resistor in the series resonant circuit. The inductance, capacitance, and resistance is determined by the character of the resonant mode fields and the electrical energy dissipation in the cavity. The coupling transformer, with turns ratio n_1, we have chosen to interpret in such a way as to introduce the nature of directivity in the resonant mode excitation. When the TM_{11} mode is travelling from left to right, then n_1 is of some appropriate finite value; for the opposite direction of TM_{11} mode travel we have no coupling and hence $n_1 = \infty$.

When the frequency of the TM_{11} mode is not within line-width of any coupled cavity resonance, then the series resonant circuit presents a large impedance to the transmission line and hence its loading effect on the transmission line is negligible. For frequency intervals where this is true the operation of the device may be explained on the basis of the non-reciprocal transmission line alone. We revert to this discussion and continue the work started in Quarterly Status Report No. 13. Equation (1.47) of QSR No. 13 predicts the power transmission coefficient of the device when the wave travels from left to right, i.e. when the line is attenuating. For convenience we reproduce the equation:

$$\mathrm{PTC} = \frac{-54.5\,b}{\beta_{11} a^2} \; \frac{\epsilon''_+}{\epsilon_0} \left[0.136 + 0.197 \frac{\beta_{11} a}{2\pi} + 0.173 \left(\frac{\beta_{11} a}{2\pi} \right)^2 \right] \qquad (1)$$

where "a" is the size of the square guide, "b" is the length of the plasma package, β_{11} is the phase constant for the unperturbed TM_{11} mode. Note that in Figure 1 we have used β_1, but that is the same as β_{11}. We write out the last factor ϵ''_+ as

$$\epsilon''_+ = \epsilon_0 \, VP^2 \; \frac{1}{(Y-1)^2 + V^2} \qquad (2)$$

where

$$V = \frac{\nu_c}{\omega}, \quad Y = \frac{\omega_H}{\omega}, \quad P = \frac{\omega_p}{\omega},$$

ν_c, ω_H, ω_p and ω being the collision frequency, electron cyclotron resonance frequency, plasma frequency, and the microwave frequency, respectively.

It is of some interest to examine the conditions under which maximum absorption occurs. Maximum absorption means minimum power transmission coefficient, and from (1) it is clear that this requires ϵ''_+ to be at a minimum. As (2) implies this demands that we set $Y = 1$, and also taking $f = 3.9$ Gc we reduce (1) to

$$\mathrm{PTC} = -4.5 \frac{P^2}{V}, \qquad (3)$$

The above formula is expressed on the db scale. The dimensions of the plasma package and the device are given in Quarterly Status Report No. 13. The fact that the magnetostatic field in our device is non-uniform increases the PTC by approximately one-half on the db scale. We introduce this factor in (3) to keep our discussion as close as possible to our experimental device. The equation (3) then becomes, when written explicitly in terms of f_p and ν_c, both measured in Gc.

$$\mathrm{PTC} = -3.6\,\frac{f_p^2}{\nu_c} \quad . \tag{4}$$

The results of this formula have been plotted in Figure 2, as lines of constant PTC; ν_c is the ordinate axis and f_p the abscissa axis. We see that increasing the plasma frequency increases the attenuation, but increasing collision frequency, decreases it. From Figure 2 one may select desirable plasma properties for specified absorption in the device.

II EXPERIMENTAL STUDY OF PLASMA PACKAGE STABILITY

At the beginning of the second quarter of this work, the Varion ion-pump mentioned in Quarterly Status Report No. 13, could no longer be pumped down beyond its ionization phase. According to the local Varian representative, the trouble was either contamination of the pump elements, or deterioration of the electrodes. Since in either case, considerable expense and time would have

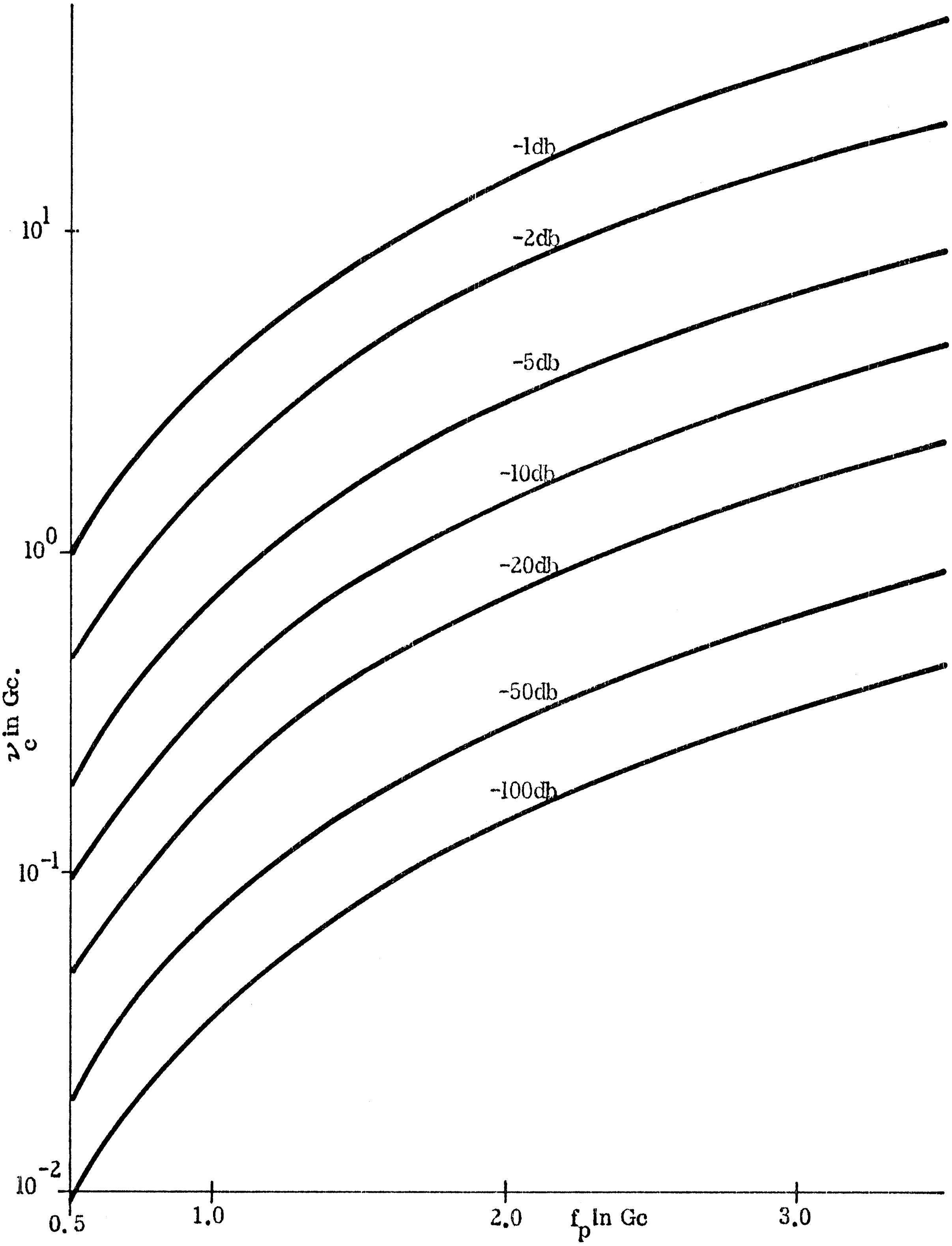


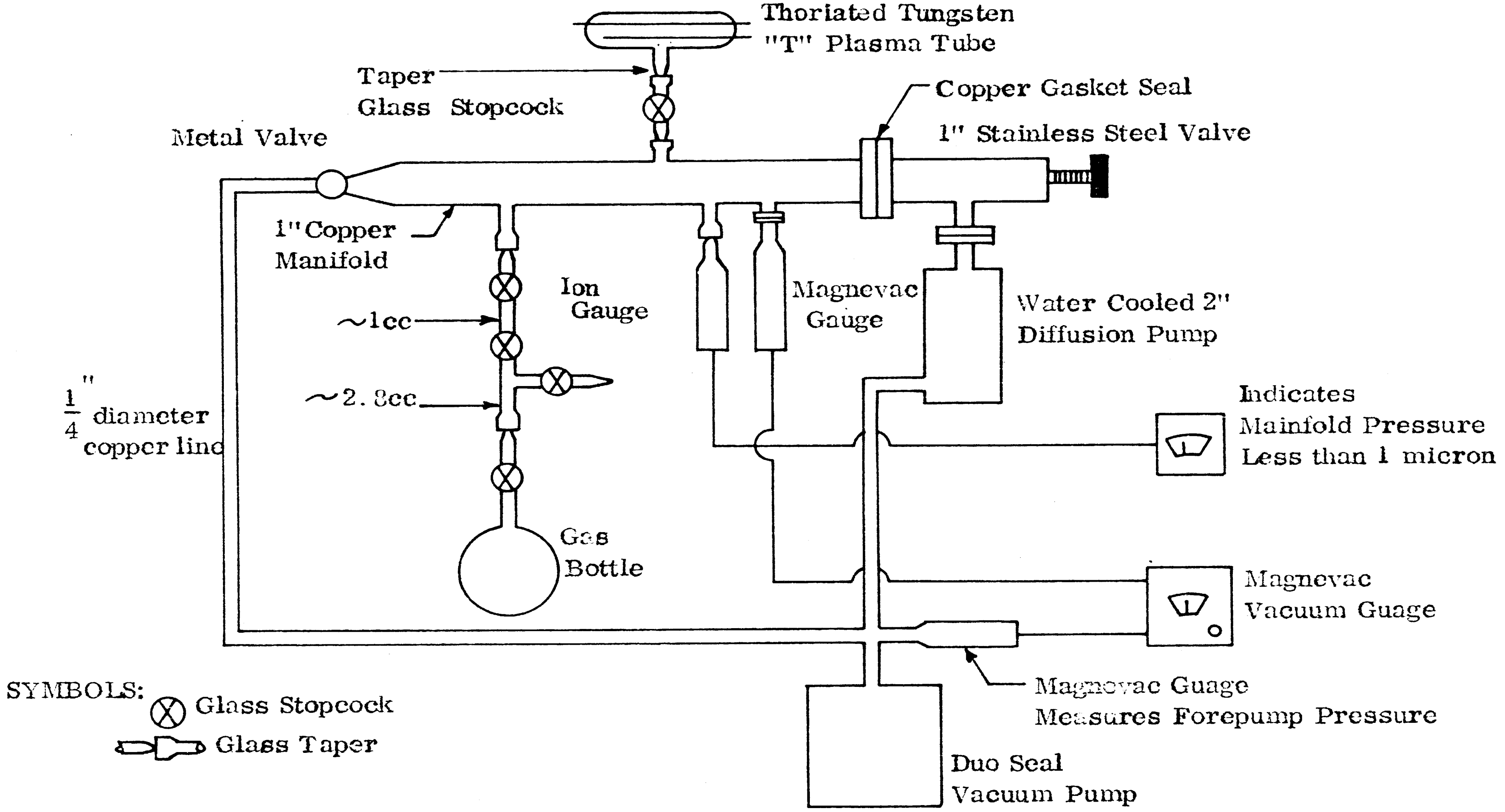
Figure 2: Minimum Power Transmission Coefficient for Nonuniform Magnetic Field As a Function of f_p and ν_c with f_c=f=3.9 Gc.

been required to put the unit back into operation, we decided to build a new vacuum station which would also be more suitable for the present application.

The vacuum station which was assembled in this past quarter consists of a Welch Fore Pump, Model 1402 and a Vacuum Instrument Research Company 2" Diffusion Pump, with a 1 inch copper manifold and various connecting fittings for the plasma chamber, gas inlet, pressure gauge ports, etc. A 1 inch stainless steel valve with teflon seat is used between the manifold and the diffusion pump. A schematic of the system is shown in Figure 3

This system has been in operation since the middle of September. Pressures as low as $3x10^{-7}$mm Hg have been obtained after baking the manifold for four days at 90 - 100° C. After valving off the manifold from the diffusion pump, the pressure has remained below $2x10^{-6}$ mm over a period of six hours, and due to the light pumping action of the ion pressure gauge, the pressure was actually decreasing at the end of this time.

A plasma envelope considerably more elaborate than the previous one has been assembled. A photograph of the plasma tube is shown in Figure 4. The tube has maximum outside dimensions of approximately 4-3/4 x 3 x 1-1/2 inches. The cathode is a direct heated Barium-Nickelate type supplied to us as engineering samples by the General Electric Company. It is the cathode used in the GE Type 5544 inert gas filled Thyratron, and has a temperature



SCHEMATIC OF
VACUUM SYSTEM

Figure 3

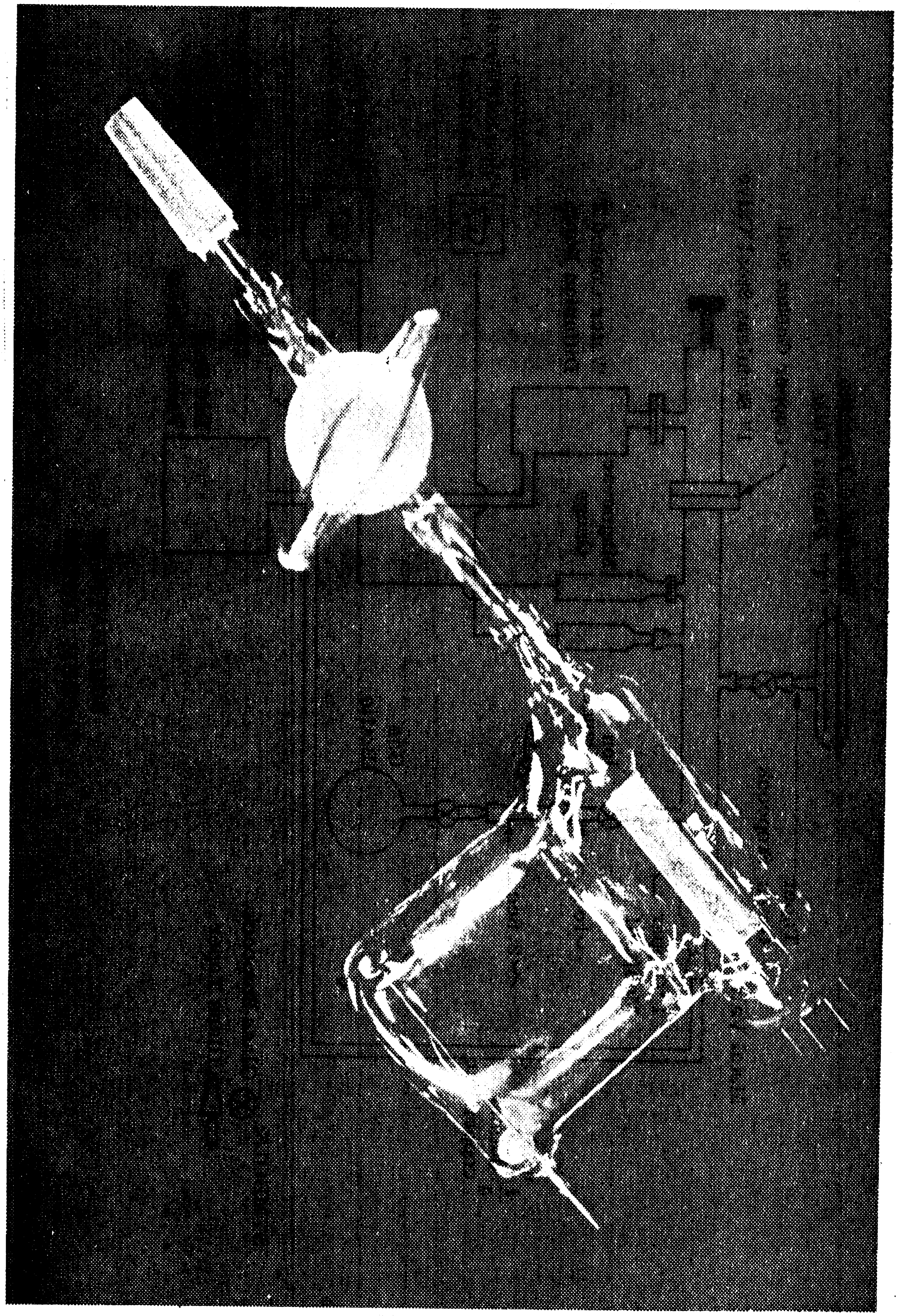


Figure 4: The Plasma Package

limited emission of 3.2 amperes. The cathode is partially shielded by a nickel heat shield, 0.005 in thick . The anode is of platinum foil 0.002 in thick. Two barium getters are also mounted at the cathode end of the tube. The entire cathode assembly is mounted on a standard eight-pin tube base that may be removed from the chamber and replaced. The nickel parts of the tube were hydrogen fired before assembly. Nickel could not be used in areas of the tube where the temperature would be less than 360°C (the Curie temperature of nickel) since the tube will be placed in a strong magnetic field. The tungsten and platinum were not fired; outgassing from these metals is not a serious problem.

One should state at this point the essential operations which have to be successfully completed before we have a useful plasma package. The first operation is to construct a slab-like diode with ample cathode area. The diode has to be well baked out to remove all the impurities after which the cathode must be developed. The slab-like form is structurally weak and thus we are limited to rather low bake-out temperatures. Second, we have to obtain a pure noble gas. The oxygen and water impurity should not exceed one part per million. Third, we have to transfer the gas via the pumping manifold to the diode without increasing the impurity levels. Lastly, we have to seal the tube from the manifold by "pulling" a glass seal.

Oxide cathodes, once they are developed, cannot be exposed to atmosphere. The coating absorbs atmospheric water and is destroyed. Thus the first step is irreversible, and we have to be sure that we can make the second and third steps before we attempt the first. For this reason a simple diode was constructed, consisting of a 4 1/2 in long cathode of two strands of 0.010 in diameter thoriated tungsten wire and an anode of 0.10 in diameter tungsten rod mounted in a glass envelope 5 in long by 1 1/4 in outside diameter. The cathode was apparently developing normally, when one of the feed-through beads developed a leak. This was repaired, and the tube put back on the system. A subsequent gas fill gave a high rate of poisoning. The problem is under investigation as to whether the gas had higher contaminant levels than expected, or if it was contaminated in the manifold.

III CONCLUSIONS

The principal interaction of the electromagnetic fields with the magneto-ionic plasma in a multimode guide can be represented by an equivalent circuit that consists of a non-reciprocal transmission line and coupled resonant circuits. Our main difficulty is now in the experimental area. The problem consists of three stages: 1) constructing a large cathode diode that is well baked out, 2) obtaining a very pure usable gas, and 3) transferring it without contamination to the diode.

IV FUTURE PLANS

In addition to the present manifold we want also to assemble a complete metal manifold system that may be baked out to higher temperatures than the present one. In addition we want to construct a plasma package with a thoriated tungsten filament. This filament may be exposed to the atmosphere when it is cold without any ill effects. The moisture of the atmosphere destroys oxide coated cathodes. On the theoretical side, further computations will be carried out on the cyclotron resonance interaction.