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MICROWAVE DIAGNOSTIC SYSTEMS AND TECHNIQUES FOR USE IN CONTROLLED FUSION RESEARCH

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ABSTRACT

Microwaves have been used for several years at Lawrence Radiation Laboratory to study conditions in the magnetically contained plasmas of controlled fusion research. There are two basic microwave techniques. One gives information on electron density and distribution in the plasma, the other provides data on electron temperature. This paper briefly summarizes the established techniques, discusses engineering requirements and limitations, and describes some further applications of microwaves presently being considered.

INTRODUCTION

Since the inception of Project Sherwood at the University of California's Lawrence Radiation Laboratory (LRL) several years ago, various diagnostic techniques have been developed by Laboratory personnel. These include the use of microwaves in diagnosing conditions of low-temperature plasmas. The purpose of this report is to summarize the engineering techniques for plasma diagnosis that have been developed by the Microwave Diagnostic Group at LRL.

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The group has drawn freely upon the experience of the Radio Astronomer and Astrophysicist for useful techniques, modifying them where necessary.

It is assumed that a plasma consists of equal concentrations of electrons and ions. Therefore if one studies the condition of the electrons in the plasma, one should determine something about the ions. What one is trying to do, of course, is to establish conditions whereby the ions created from a gas such as deuterium will be fused to create a heavier atom and at the same time release energy which can be extracted and used. One might then ask: Why not throw out the electrons and forget about them since one is interested in ions and not electrons? The answer is that the electrons, being of opposite sign to the ions, are left in the mixture to cancel part of the tremendous Coulomb repulsion between ions. Otherwise one would have to add tremendously large amounts of energy to the ions to move them close enough to each other so that fusion can take place. It is doubtful if fusion would ever take place in the laboratory if the electrons were removed. It should be evident then that a study of the behavior of the electrons will also yield some data about the ions.

There are basically two techniques in microwave plasma diagnosis. One is for measurements of electron temperature, the other for obtaining data on electron density and distribution. They will be separately described.

Microwave plasma diagnosis is expensive because of the high cost of the equipment. Its great advantage is that it produces minimum disturbance of the plasma--in contrast to a probe which greatly perturbs the plasma and, being partly destroyed in the process, contaminates and cools it.

SYSTEMS FOR DETERMINING ELECTRON DENSITY AND DISTRIBUTION

Theory. Wharton[1] has examined the theoretical aspects of propagating microwaves through a plasma for the purpose of measuring electron density. He assumes the plasma to be a dielectric whose dimensions are large compared to the cross section of the beam of the radiating antenna. He then proceeds to develop relatively simple expressions for the propagation coefficient by making certain simplifying assumptions, considering both the case where the external magnetic field is parallel to, and the case where it is perpendicular to, the electric vector of the microwave. The perpendicular case is dismissed here because it contains a pole at the electron cyclotron frequency which would mask out measurements at or near that frequency.

For the external magnetic field parallel to the electric vector of the microwave, and with collisional damping neglected, the expression for the propagation coefficient becomes

$$\Gamma = \alpha + j\beta. \tag{1}$$

The attenuation constant α tends to zero, and the phase constant β reduces to

$$\beta = \frac{\omega}{c}\sqrt{K} = \frac{\omega}{c}\sqrt{1-\omega_p^2/\omega^2}\ , \tag{2}$$

where ω = microwave radian frequency,

c = velocity of light,

K = plasma relative dielectric constant,

ω_p = plasma frequency = $\sqrt{ne^2/m\epsilon_0}$

In the expression for plasma frequency (ω_p),

n = electron density (electrons per cm^3),

e = electron charge (1.6×10^{-19} coulomb),

m = electron mass (9.11×10^{-31} kg),

$\epsilon_0 = \frac{1}{36\pi} \times 10^{-9}$ farads per meter.

The phase shift of the microwave as a result of passing through the plasma is expressed by

$$\Delta\phi = \frac{2\pi d}{\lambda}\left(1 - \sqrt{1 - \omega_p^2/\omega^2}\right). \qquad (3)$$

where d = thickness of plasma in meters,

λ = microwave wavelength in meters.

Thus we see that measurement of the phase shift will enable us to determine the electron density n, since all the other parameters in equation 3 are known or measurable. Wharton and Slager[2,3] have experimentally verified the theory and developed techniques and circuitry which are in extensive use.

Engineering Requirements. Knowing the conditions under which the systems are to be used, one can proceed to specify certain requirements which the equipment must meet. They are as follows:

1. *Very wide bandwidths* are required because of transients which develop on machines that are pulsed. Most of the machines in the Pyrotron Program are pulsed; an exception is the P-4 machine.
2. *Large dynamic range* is needed: 0 to 10^3, millivolts to volts for video amplifiers.
3. *Good frequency stability* is essential, because phase shift--the thing being measured--is frequency dependent.
4. *Low ripple and noise* must be maintained for accurate measurement of phase shift.
5. *Precise sweep circuits* are needed. They should be very linear, free from hum and drift, and of fixed dc level.

Mismatch in the transmission path is not important, because the reflections it might produce are masked out by multiple reflections from the complex plasma surface. Nor are extremely accurate measurements required, in view of the simplifying assumptions and the limited accuracy of other measurements used in the calculations.

Limitations. There are certain basic limitations to the use of the microwave method. First, it must be restricted to plasma beams of solid cross section. It can not be used for hollow beams due to the fact that the region inside the hollow beam is inaccessible to the microwave at cutoff. Second, when a strong external magnetic field constricts the plasma so much that its diameter is no longer large compared to the antenna beam cross section, then the microwave energy scatters around the plasma column. This causes large errors in the measured phase shift. Third, extremely high frequencies are required when particle densities in excess of 10^{14} are achieved. This is demonstrated in Fig. 1 where particle density is plotted against frequency: For very high densities the frequencies that would be required are beyond the present "state of the art." Fourth, microwave components are very expensive and thus sizable amounts of money are required to set up a system for a measurement. And fifth, high-caliber personnel are required to operate the equipment because of its complexity.

Description of the Systems. Figure 2 shows the fundamental bridge used in the fringe shift presentation. With the plasma turned off, the bridge is balanced with the variable attenuator and phase shifter in the null path. When the plasma is turned on, the bridge unbalances and balances successively giving rise to an oscillogram such as that shown in Fig. 3. This is interpreted by use of the experimental methods developed by Wharton and Slager.

Another circuit which overcomes the need for a very stable frequency, eliminates the amplitude effects shown in Fig. 3, and permits rapid data reduction is shown in Fig. 4. In this circuit, one arm of the bridge is made several hundred wavelengths longer than the other arm, and the frequency of the klystron is swept back and forth about 50 mc/sec by modulating the repeller. The phase of the signal in the long path varies more rapidly causing the bridge to balance and unbalance successively as the two signals interfere with each other. The interference signals are detected, amplified, clipped, and used to intensity-modulate the scope. The klystron sweep voltage is also applied to the y axis of the scope which is swept internally on the x axis. A series of dots appears. When the appropriate time base is applied to the x axis, the dots smear out into a set of bars when no plasma is present. When the plasma is introduced, the bars shift or skew as seen in the oscillogram shown in Fig. 5. The data interpretation is similar to that of the fringe shift method. Figure 6 shows a typical interferometer installation.

Figure 7 shows an interconnection diagram of the various circuits used in presenting the data for either of the two methods described. The power supplies and regulators are standard laboratory designs modified where necessary. The sweep and trigger generator and the push-pull amplifier and clipper were designed by members of the diagnostic group. The complete circuits, not shown here, have been published in a report by the author.[9]

SYSTEMS FOR DETERMINING ELECTRON TEMPERATURE

Theory. In measuring electron temperature, one may regard the plasma as a blackbody and apply Planck's radiation law.[1] The power received by a linearly polarized receiver in the near zone may be approximated by the expression

$$P_n = \left[K\,T_e\right] \Delta f \left[1 - e^{-ad}\right], \qquad (4)$$

where $K = 1.38 \times 10^{-23}$ joule/°K,

T_e = electron temperature in °K,

Δf = bandwidth of receiver in cps,

a = plasma absorption coefficient, nepers/meter,

d = thickness of plasma sample in meters.

Dispersion effects of the plasma are shown in Fig. 8. It is seen that there is dielectric singularity at the cyclotron frequency, and conditions are most favorable for radiation at this frequency. To determine the proper receiver frequency for studying plasma radiations, one first determines the value of the magnetic field used for containment, and then calculates frequency from the equation

$$\omega_c = (e/m) \times B, \tag{5}$$

or more simply,

$$f_c = 2800 \text{ mc} \times B_{KG}. \tag{6}$$

Description of the System. The receiving system for determination of electron temperature consists of a receiving antenna which "looks" at the plasma radiation, a high-quality radar receiver, and a means of calibration. Figure 9 shows in block diagram the setup for measuring temperature.

A typical receiver at 35,000 mc constructed for use on certain experiments has a measured noise figure of 5 db. This figure, of course, may be in error as much as 2 db because of measurement inaccuracies or inaccuracy of the calibrating standard. But it is a good receiver judged by standards prior to parametric amplifiers. The sensitivity of such a receiver with an IF bandwidth of 2 mc is about −109 dbm.

The electron temperature measurement is no more complicated than any other communication measurement. However, one must calibrate the receiver. This is done with a standard noise diode. The noise diodes in use at LRL have about 1 ev (11,600°K) excess noise. The signal in the signal-arm input to the balanced mixer is modulated by a mica wheel inserted in a slot in the waveguide. Strips of Aquadag are painted on the wheel which is spun by a motor. Light from a source situated on one side of the wheel is picked up by a photocell on the other side. The photocell's output is used to trigger the scope.

A circuit recently developed by a member of the Diagnostics Group can be used to replace the mechanical modulator. This circuit is used to electrically modulate the signal, thus allowing a completely inclosed waveguide system.

If one calls the amplitude of the received signal D, the equation for the power received reduces to

$$P = P_1 \left[\frac{D - D_0}{D_1 - D_0}\right]^2 \qquad (7)$$

when one assumes αd (in equation 4) to be very large. D_0 is the receiver background noise, D_1 is the amplitude of signal due to the noise source, and P_1 is the noise power from the calibration source. For a 1-ev noise source, the electron temperature is

$$T_e = 1 \text{ ev} \left[\frac{D - D_0}{D_1 - D_0}\right]^2 . \qquad (8)$$

Figure 10 illustrates the quantities D_0 and D_1.

OTHER EXPERIMENTAL APPLICATIONS

Synchrotron Radiation Experiment. Some scientists believe a large part of the power produced by machines such as the Mirror machines and Stellerator machines will be radiated through a phenomenon known as "synchrotron radiation." Should this prove correct, the machines might never produce economical power. Radiation would occur at the electron cyclotron frequency (ω_c) and integral multiples thereof.

An experiment has been proposed to measure the relative amounts of power radiated by the present machines at the cyclotron frequency and its first two harmonics. The Diagnostics Group has attempted to develop a receiver which would be used to look at radiation from the plasma at frequencies ω_c, $2\omega_c$, and $3\omega_c$. Since the power radiated would be at exact multiples of the cyclotron frequency, a common local oscillator supplying fundamental, 2nd, and 3rd harmonic power should be used. This is seen is block diagram in Fig. 11. Such a receiver was constructed using commercially available frequency multipliers. It is shown in a bench setup in Fig. 12. The noise figure for the harmonic receivers is around 28 db, so these receivers are not particularly sensitive.

We have proposed building a receiver using backward wave oscillators for the local oscillator, and have determined suppliers. The backward wave oscillators would be triggered on at the same time and swept in frequency several times during a machine cycle to insure that if radiation occurs at some particular time in the cycle and not uniformly, it would be seen. No action has yet been taken on this proposal.

Colliding Plasma Experiment. An experiment has been designed for measuring the radiation that occurs when two plasma sources are fired from opposite ends of the machine simultaneously. A receiving system was supplied by the Diagnostics Group for measuring this radiation. Helical antennas were designed for frequencies of 1100 and 1660 mc, corresponding to magnetic fields of 395 and 593 G. The receiving system consisted of a 6BM6 local oscillator klystron in an Amerac 198A cavity, an Admittance Namco Model CX-7 mixer, a commercial klystron power supply, and a commercial IF strip. This receiver had a noise figure of about 8 db.

Plasma Instability Experiment. An experiment has been designed to determine the effects of the interaction of an electron beam with a plasma. The possible effects are heating and excitation of waves on the plasma. An Eimac electron gun (4K 50,000 LQ) will be fired into the end of the P-4 plasma column. Figure 13 shows the mounting structure where the gun is fired into the plasma column.

A swept frequency receiver has been designed which will look at the plasma at a point along the machine when the electron beam is fired into the plasma column. This receiver, shown in block diagram in Fig. 14 and in a picture of the mixer in Fig. 15, has a noise figure that ranges from 5.5 to 9 db over the 2500- to 4000-mc band. It corresponds closely to the receiving systems described for measuring electron temperature, with the exception of the swept local oscillator. A QK518 serves as the local oscillator, and a leveling system consisting of a traveling wave tube amplifier and an automatic gain control assembly is used.

Experiments with Low-Loss Waveguides. Usually a microwave system installation for the measurement of electron density is made several feet away from the machine being probed. (The system can not be situated at the machine because of the high magnetic fields and the subsequent danger of coil blowup.) Length of transmission path is no problem for densities requiring frequencies up to the K_a band. However, not enough power is available at 4 mm to withstand the high transmission losses in a rectangular waveguide over the required few feet of travel. The author has spent a considerable amount of time in the past year investigating the design of low-loss waveguide units. For the TE_{01} family, the Bell Laboratories design and a design by Marié described in U. S. Patent 2,859,412 have been started in fabrication by the Sherwood Electroforming Shop. These have not been checked.

A design by Microwave Associates for 8 mm has been constructed and checked. It is shown in Fig. 16. The loss per unit is about 0.3 db with a bandwidth of 6%. This is a resonant slot structure which transforms the TE_{10} mode of rectangular guide to the TE_{01} mode of round guide. The 0.634-in. inside diameter of the waveguide was chosen to eliminate all modes of the TE_{0n} family except the TE_{01}. Measured loss through the units and 10 ft of pipe was less than 1 db, most of which occurred in the transition units.

Another unit, built to this same Microwave Associates design but scaled to 4 mm, does not yield comparable results at present.

Another type of low-loss waveguide known as H-guide has been investigated. This was predicted by Tischer[6,7] and has been investigated by him and by Griemsmann and Birenbaum.[8] It consists of two parallel planes separated by a strip of dielectric used to destroy TEM modes. A design for launching into H-guide from rectangular waveguide is described in an LRL Electronics Engineering Department report. This design is approximately one foot in length; shorter lengths were too lossy. The loss per unit at 35,000 mc is about 0.6 db, and a loss per foot of about 0.2 to 0.3 db was measured in the H-guide proper. This is about the same as for the rectangular RG 96/U waveguide.

Attempts to scale this design directly to 70,000 mc were unsuccessful. Measurements were then made on the 35,000-mc design at 70,000 mc. A transition unit from RG 96/U to RG 98/U was used for launching the 70,000-mc energy. The measured loss per horn at 70,000 mc was about 1.2 db, and the loss per foot in the H-guide was 0.05 db, only one-tenth the loss in the rectangular waveguide. It therefore appears that H-guide might be successfully used for transmitting 70,000-mc energy for measurements where this high frequency is required. The H-guide does not, however, seem to be as good as the TE_{01} guide. This can be explained by dielectric losses in the H-guide.

ACKNOWLEDGMENTS

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questions and is responsible for development of much of the circuitry described. Bill Cummins, Toy Top Physicist, and Andy Gardner, who is in charge of P-4, have also been very helpful and have answered many questions. The help Ralph Senechal, Electronics Department Engineering Aid, has given in making breadboards and electrical measurements is gratefully acknowledged. Thanks are also due to Chuck Pon, Electrical Engineering graduate student at Berkeley, who made many of the measurements on the synchrotron radiation receiver.

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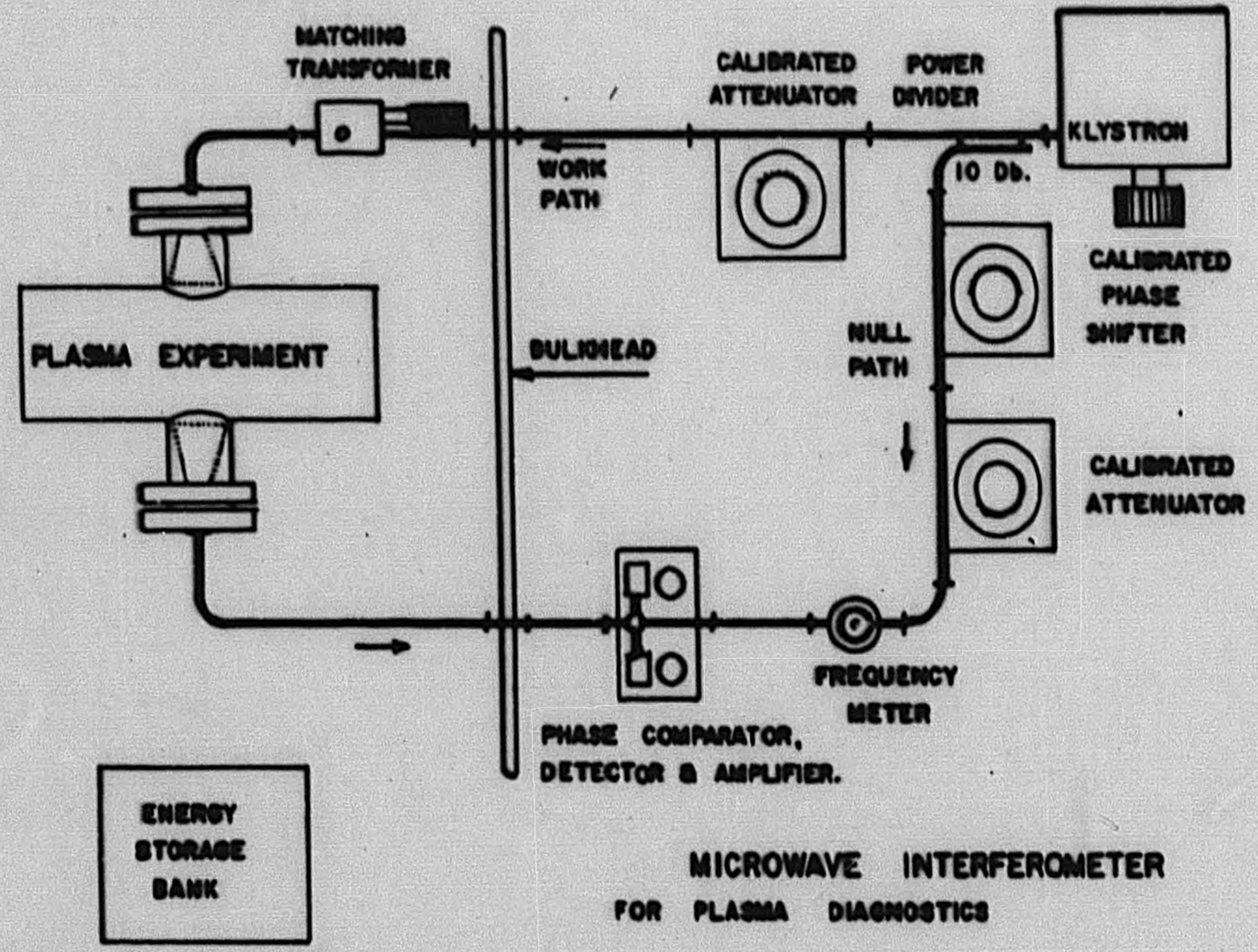
FREQUENCY KMC	MAXIMUM DENSITY ELECT./CC	MINIMUM DETECTABLE DENSITY (π/10 PHASE SHIFT) ELECTRONS/CC			
	(CUTOFF)	1" Path	3" Path	6" Path	9" Path
2.5	7.7×10^{10}	3.7×10^{10}	1.2×10^{10}	6.2×10^{9}	4.1×10^{9}
10	1.2×10^{12}	1.5×10^{11}	5×10^{10}	2.5×10^{10}	1.6×10^{10}
25	7.7×10^{12}	3.7×10^{11}	1.2×10^{11}	6.2×10^{10}	4.1×10^{10}
35	1.5×10^{13}	5.2×10^{11}	1.7×10^{11}	8.7×10^{10}	5.8×10^{10}
50	3.1×10^{13}	7.4×10^{11}	2.5×10^{11}	1.2×10^{11}	8.2×10^{10}
70	6.1×10^{13}	10^{12}	3.5×10^{11}	1.7×10^{11}	1.2×10^{11}
100	1.2×10^{14}	1.5×10^{12}	5×10^{11}	2.5×10^{11}	1.6×10^{11}
150	2.8×10^{14}	2.2×10^{12}	7.4×10^{11}	3.7×10^{11}	2.5×10^{11}
250	7.7×10^{14}	3.7×10^{12}	1.2×10^{12}	6.2×10^{11}	4.1×10^{11}

MUL-5145

Fig. 1. Microwave frequency required for transmission through a plasma as a function of the plasma electron density.



MUL-4939

Fig. 2. Microwave bridge circuit with plasma sample in one arm.

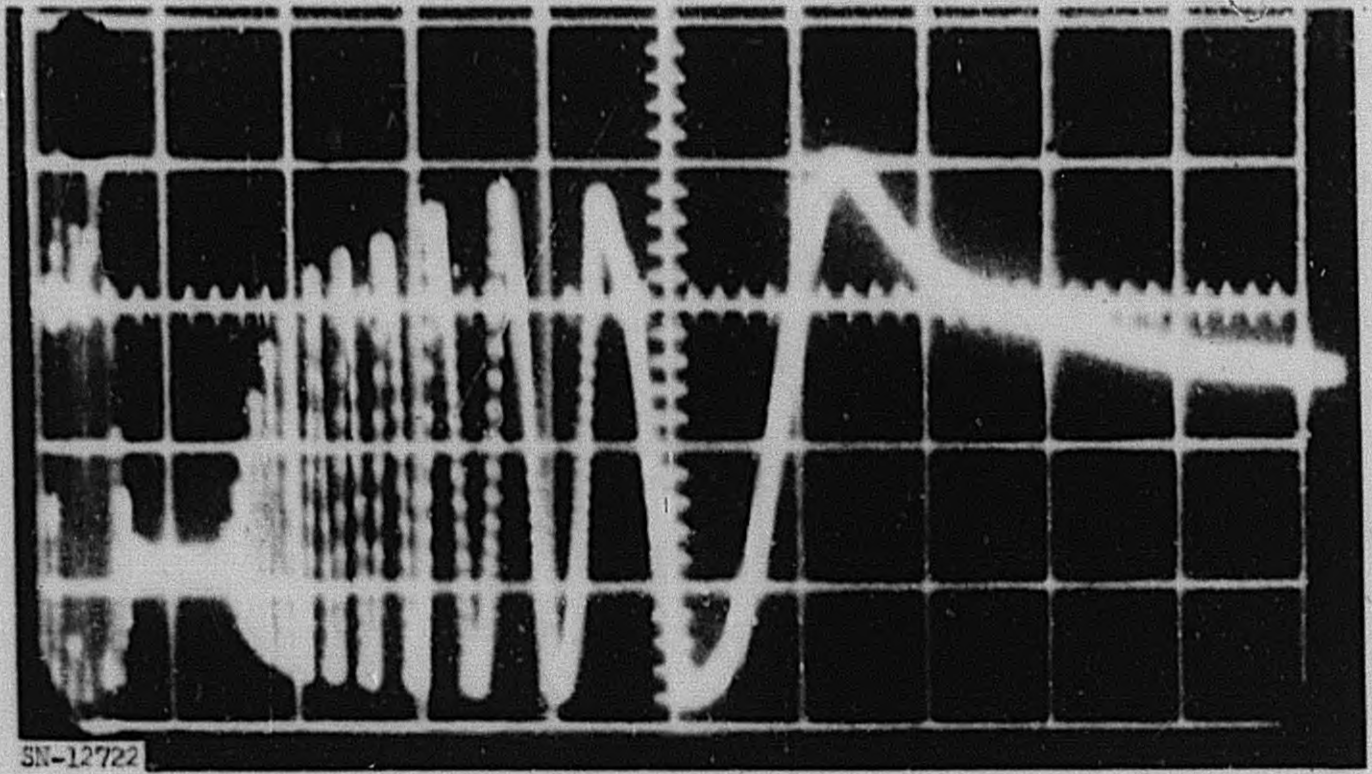
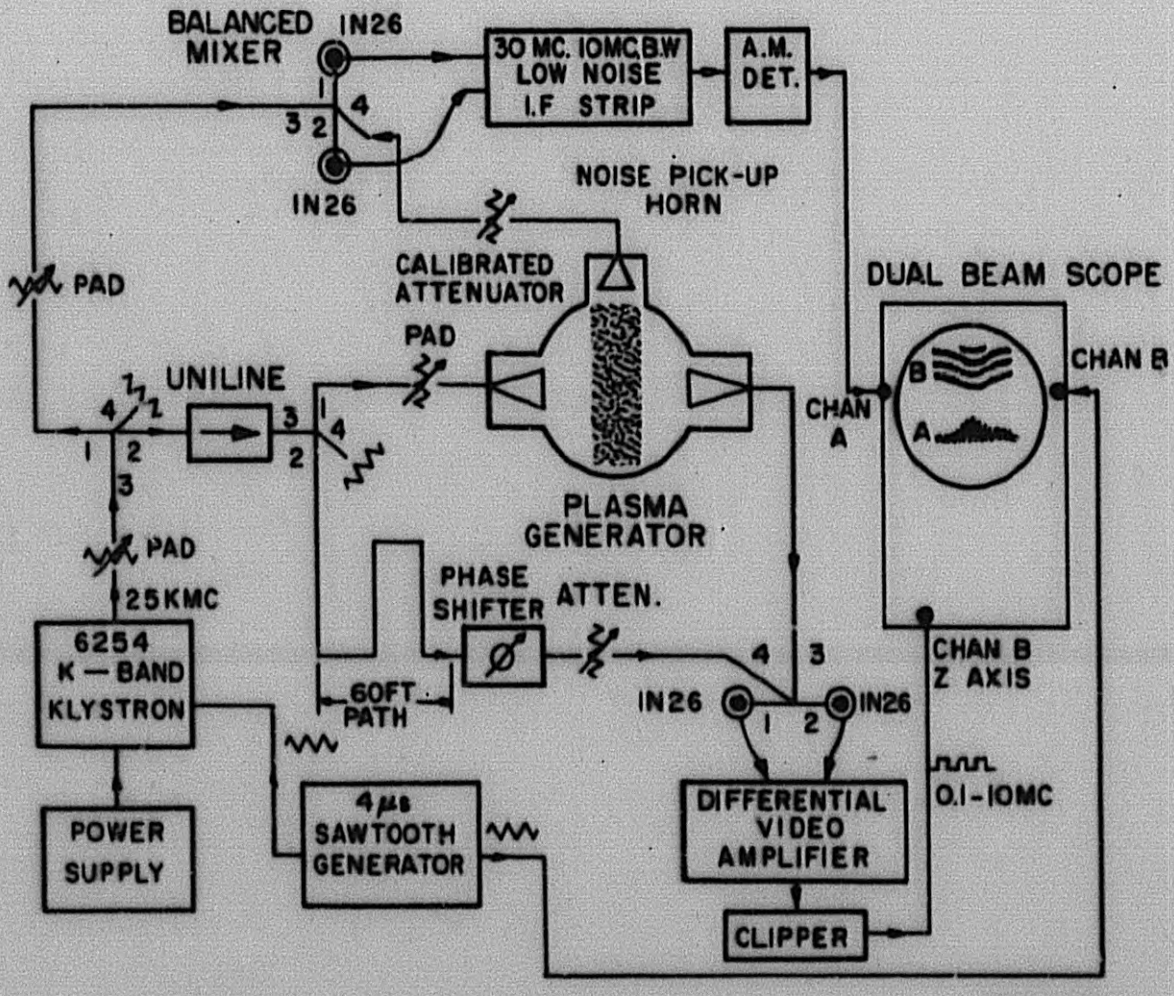


Fig. 3. Oscilloscope record of a microwave interferometer response to a transient plasma.



MUL-4399

Fig. 4. Microwave fringe-shift interferometer circuit for plasma density determination.

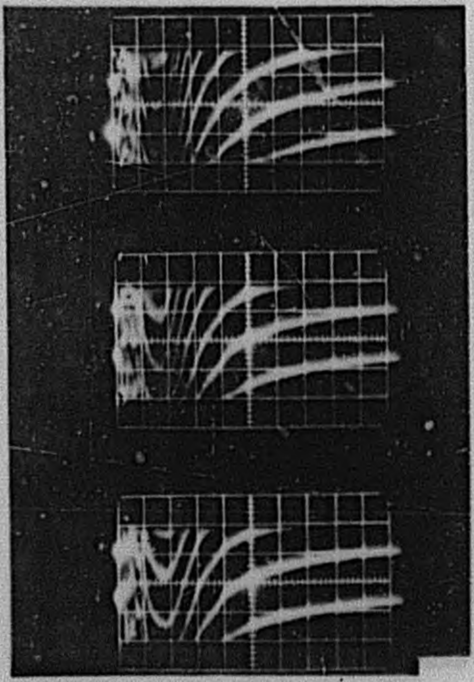
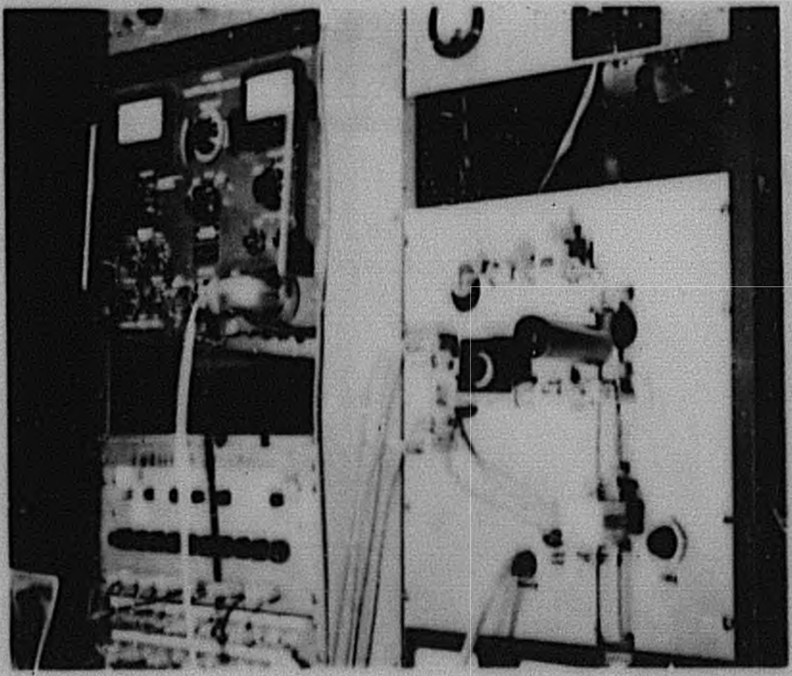
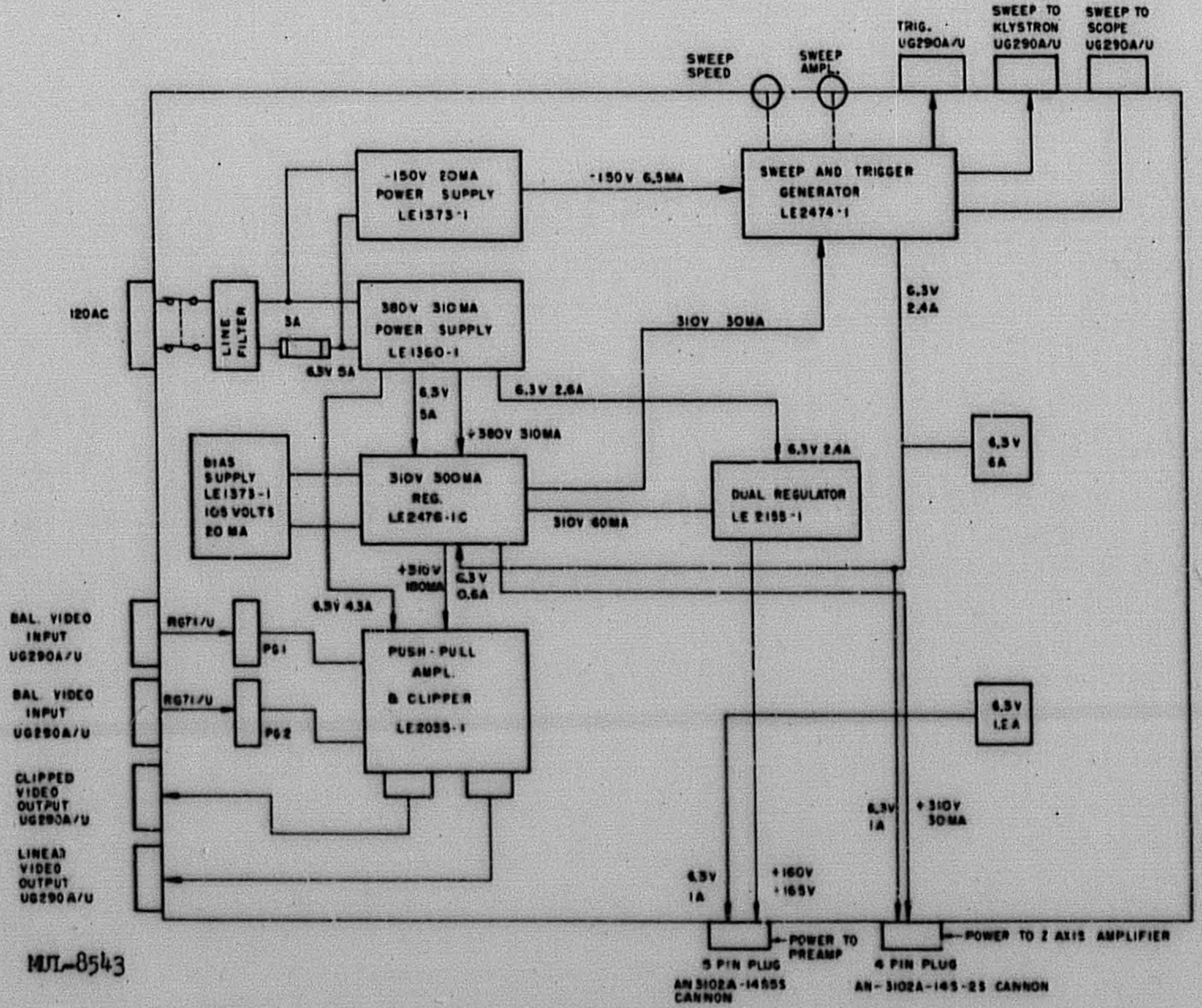


Fig. 5. Interferometer fringe-shift presentation.



ZN-21107

Fig. 6. Typical interferometer installation.



MUL-8543

Fig. 7. Interconnection diagram of circuits used in plasma electron density presentation.

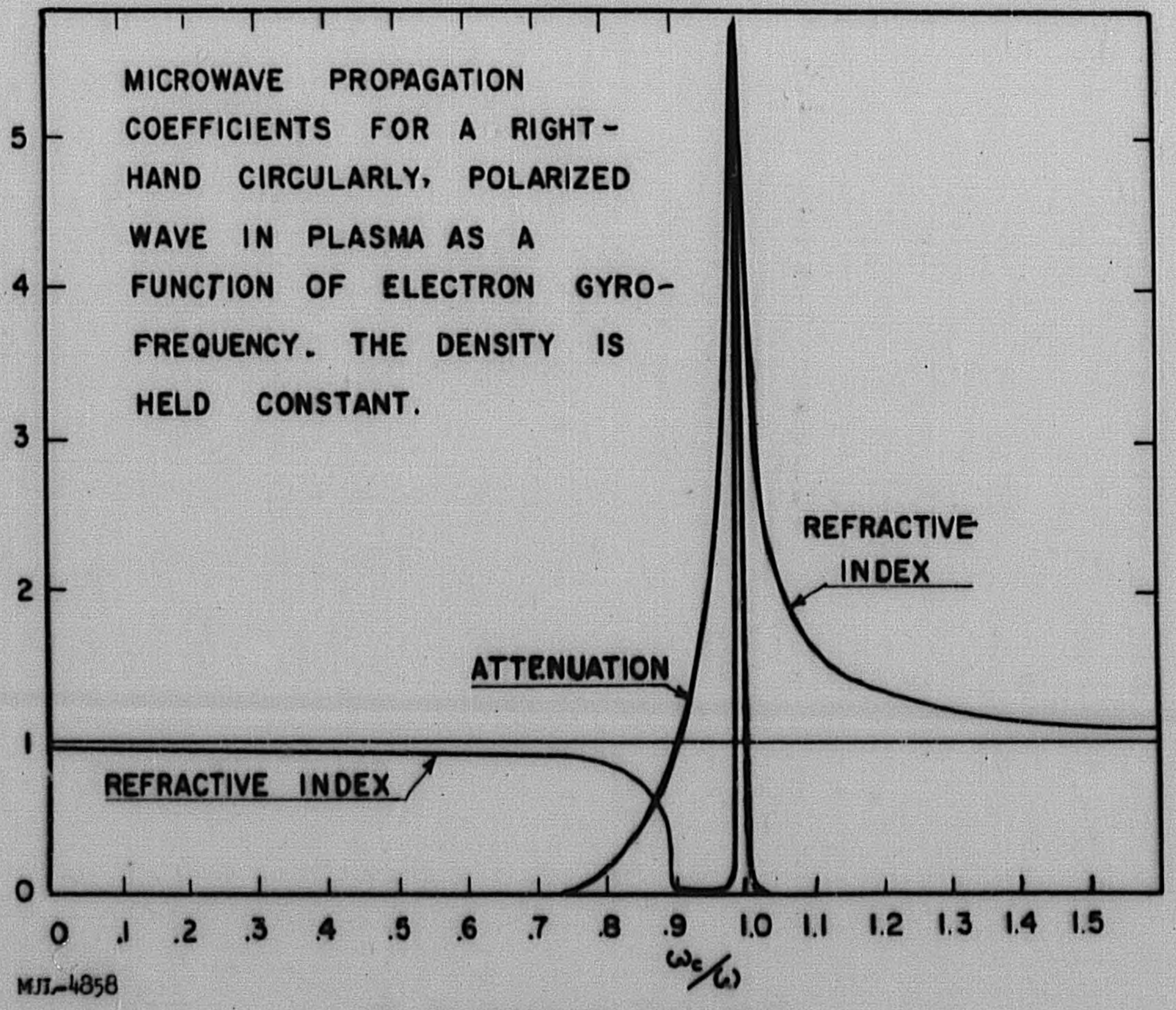
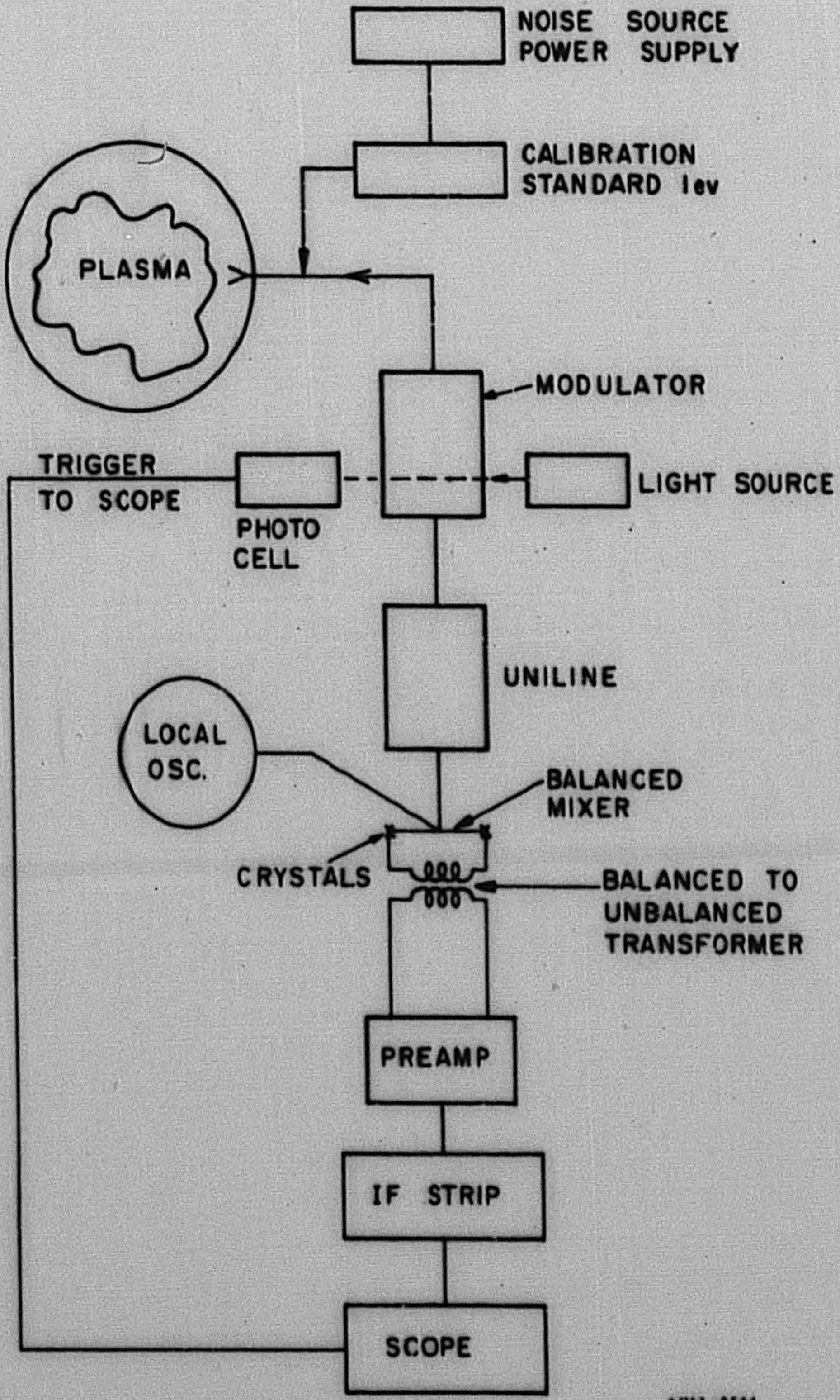
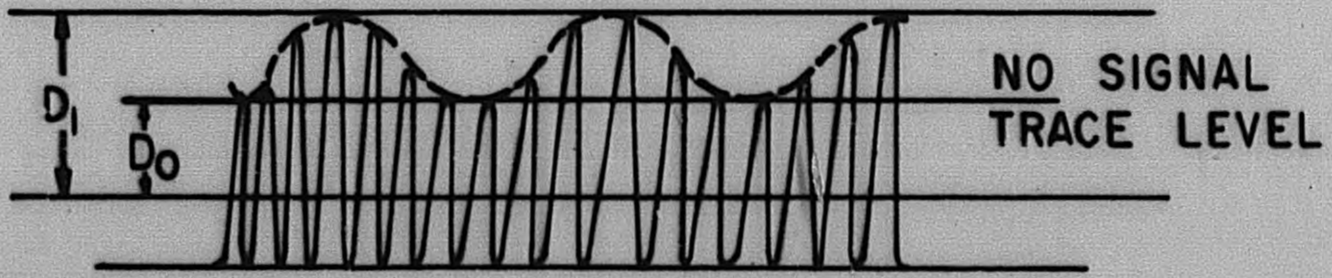


Fig. 8. Plasma dispersion effects.



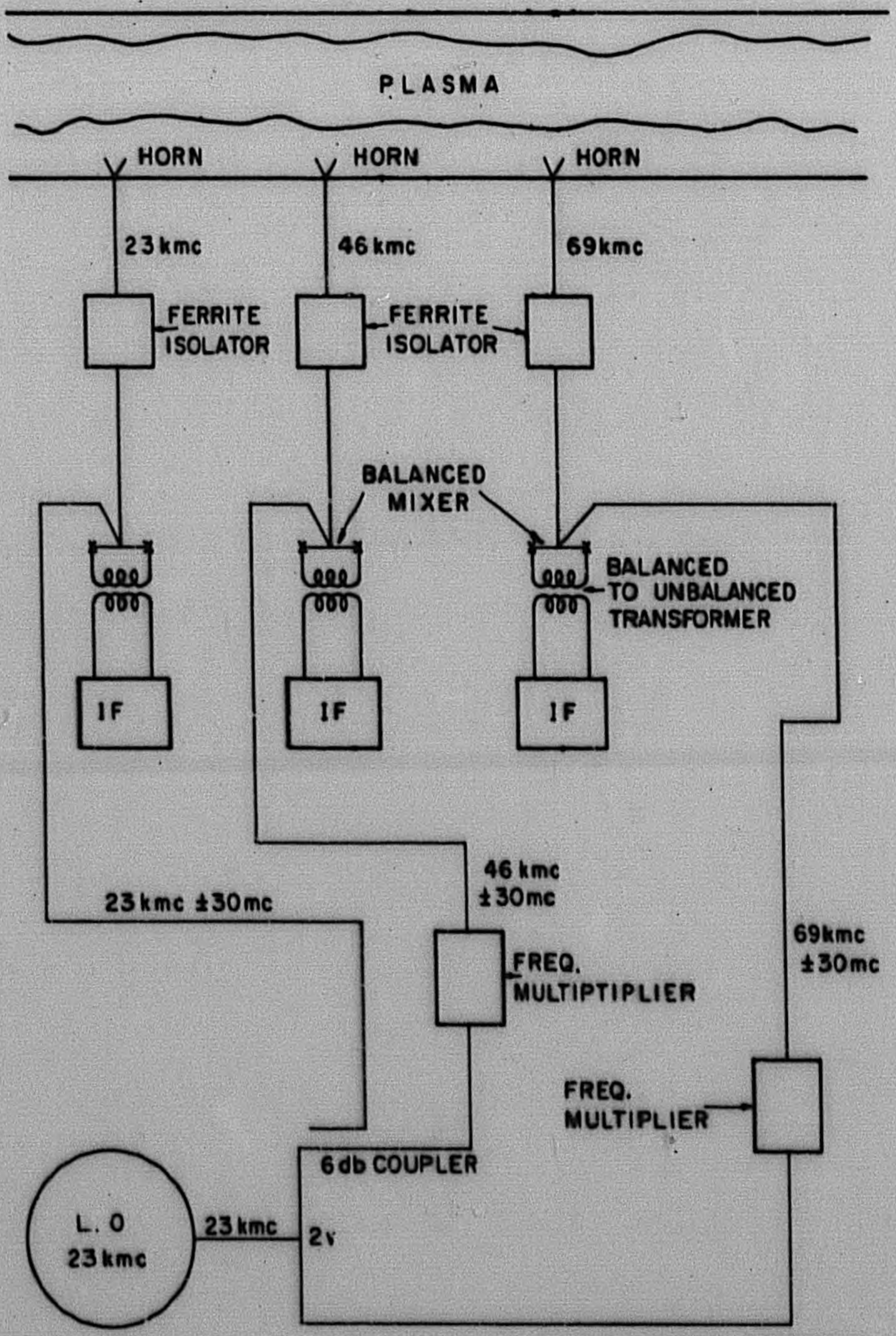
MUL-8544

Fig. 9. Block diagram of a microwave receiving system for measuring electron temperature.



MUL-8545

Fig. 10. Plot of modulated noise receiver output.



MUL-8546

Fig. 11. Block diagram of harmonic receiver for studying synchrotron radiation. (The three microwave horns are actually in a plane perpendicular to the plasma column so they can all "look" at the same portion of the plasma; they are spaced around the circumference of the plasma column.)

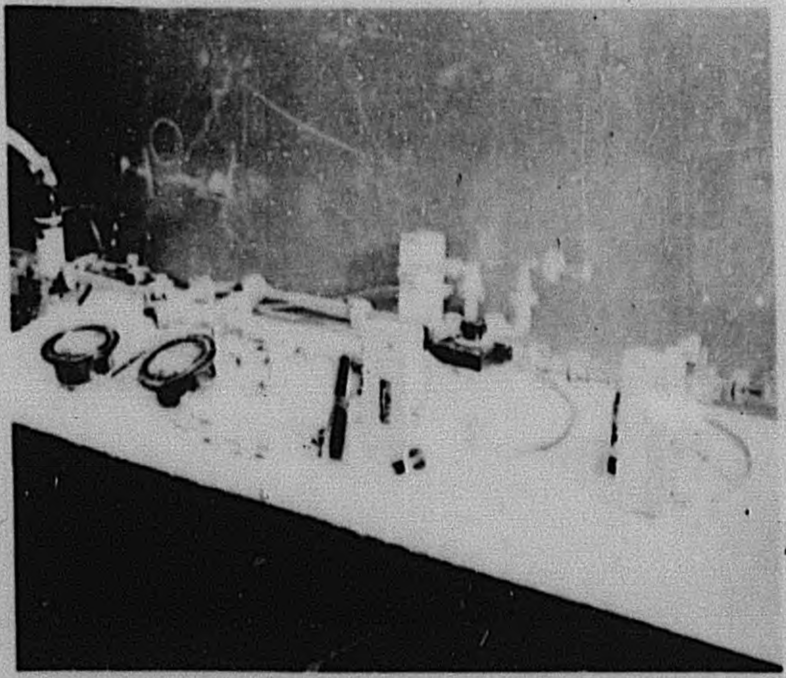


Fig. 12. Harmonic receiver in a bench setup. SN-21108

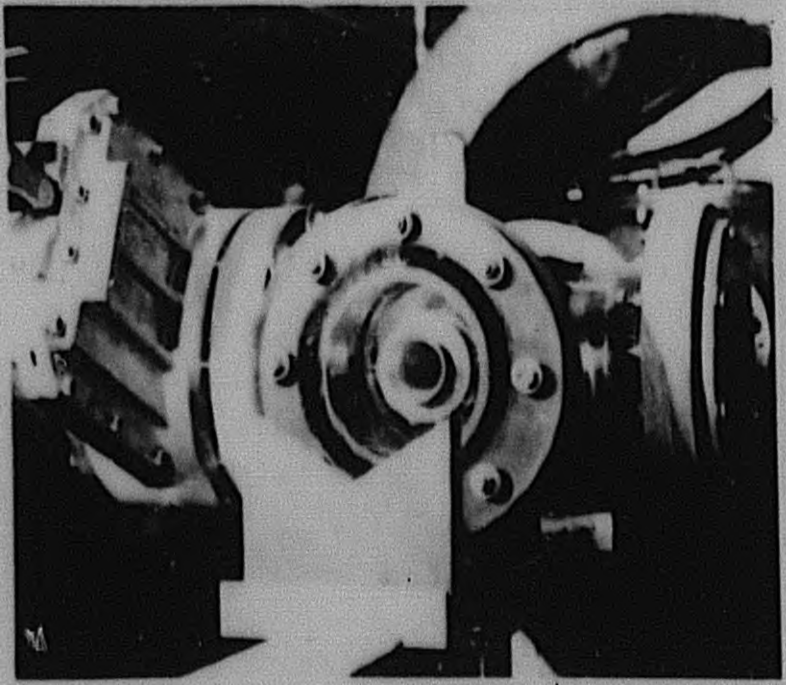
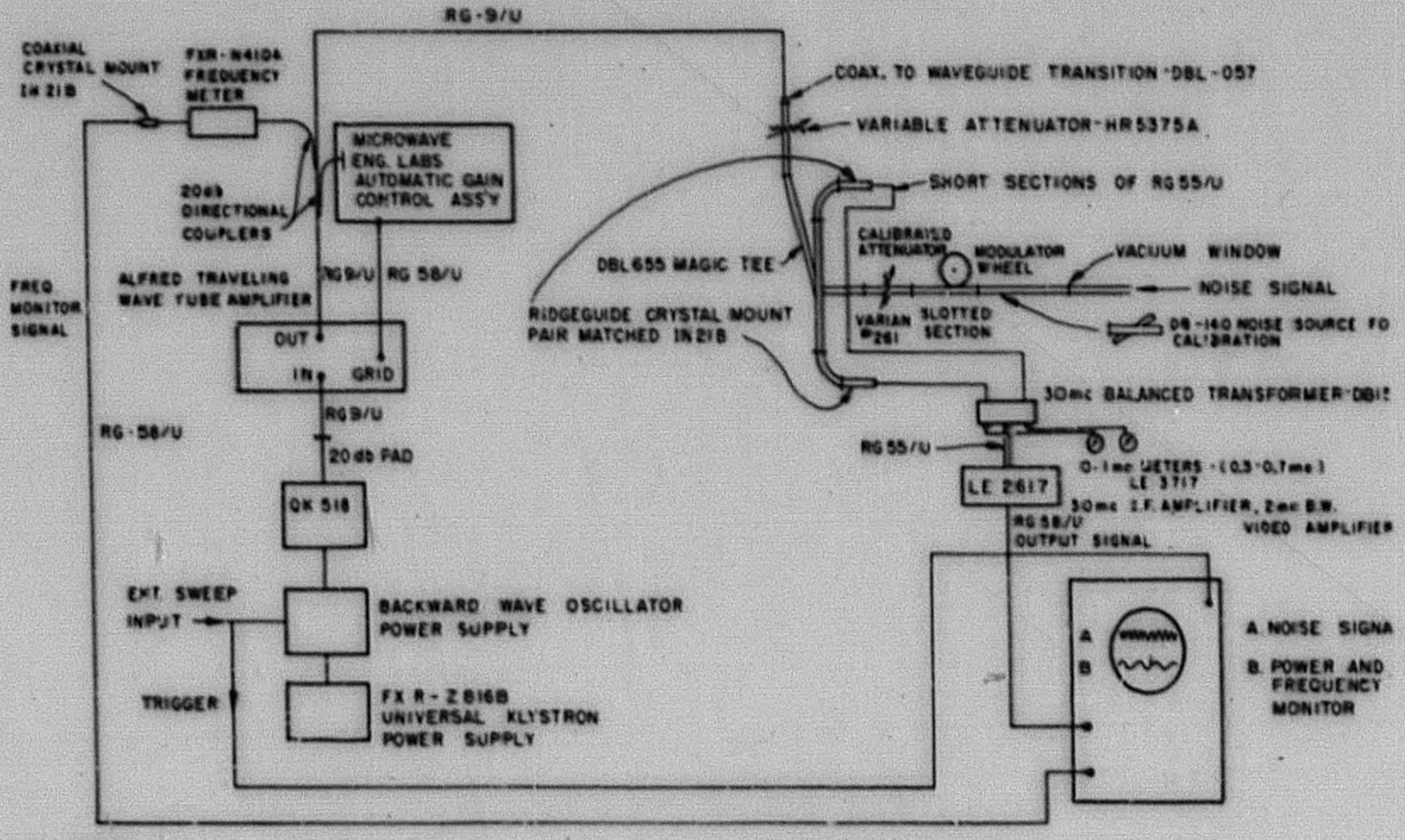


Fig. 13. Mounting structure showing where electron beam will be fired into P-4 plasma column. SN-21109



MU-8547

Fig. 14. Block diagram of S-band swept-frequency receiver for studying radiation from a plasma.

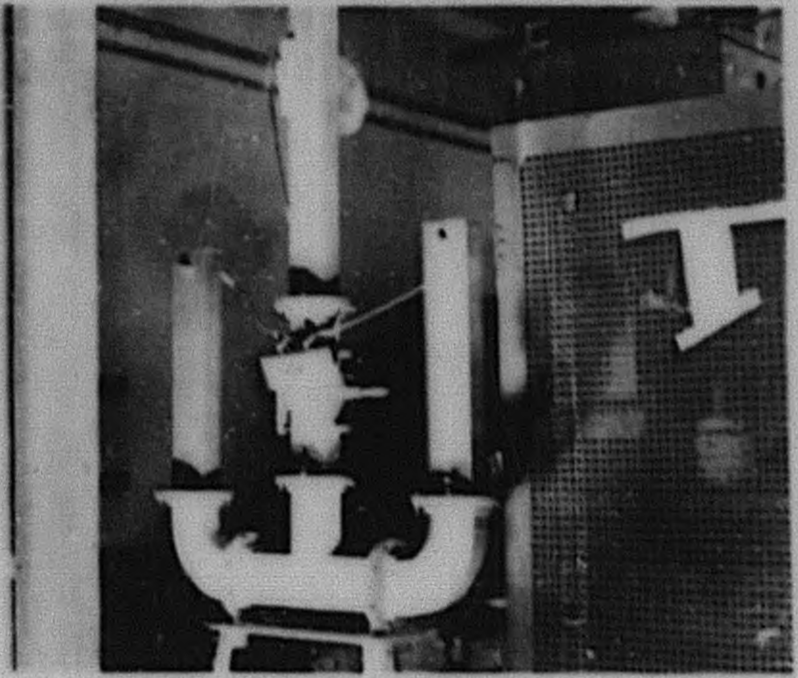


Fig. 15. Picture of mixer assembly used with receiver shown in Fig. 14. SN-21110

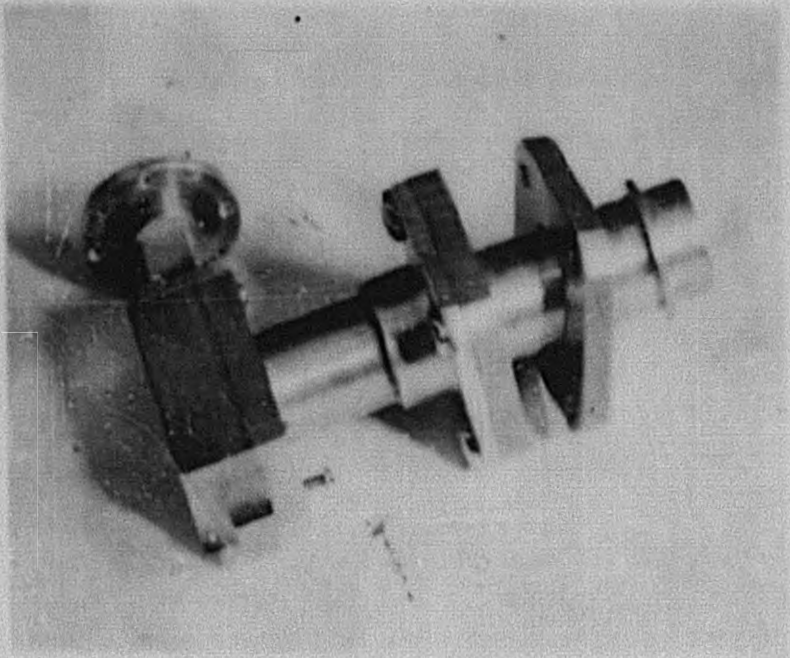


Fig. 16. Picture of resonant slot structure for launching TE_{01} mode from rectangular waveguide. SN-21111