

March 12, 1968

P. P. KEENAN ETAL

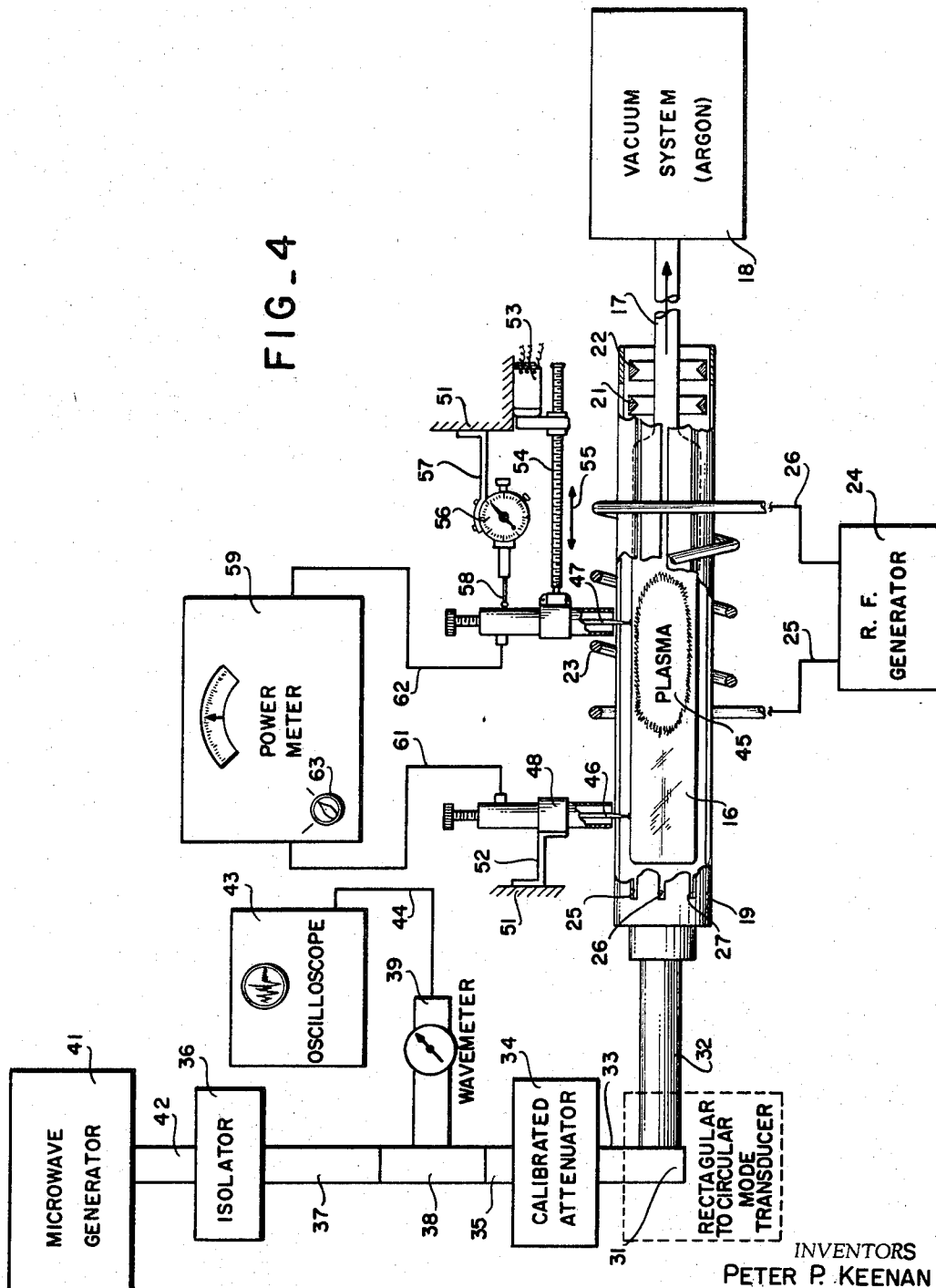
3,373,357

CONTROLLED MODE PLASMA DIAGNOSTIC APPARATUS

Filed Jan. 4, 1965

2 Sheets-Sheet 2

FIG. 4



INVENTORS

PETER P. KEENAN

FRANK L. KELLY

By *George C. Sullivan*
Agent

1

3,373,357

CONTROLLED MODE PLASMA DIAGNOSTIC APPARATUS

Peter P. Keenan, Van Nuys, and Frank L. Kelly, Granada Hills, Calif., assignors to Lockheed Aircraft Corporation, Burbank, Calif.

Filed Jan. 4, 1965, Ser. No. 422,959

10 Claims. (Cl. 324—58.5)

ABSTRACT OF THE DISCLOSURE

An electrodeless discharge plasma is generated by induction in a low-pressure gas confined within a slotted circular waveguide. Microwave energy at a selected probing frequency is then propagated in the TM_{01} mode through the waveguide, and hence through the plasma, to permit measurement of various plasma phenomena. Propagation characteristics, plasma density profiles and other measurements are obtained by means of a fixed antenna probe and a movable antenna probe. Both of these probes extend through the slotted wall of the waveguide and provide signals to ancillary indicating devices.

This invention relates to a method and apparatus for the investigation of plasma phenomena of the electrodeless discharge type and more particularly to a controlled mode plasma diagnostic technique and slotted waveguide apparatus therefor.

Prior to the present invention there has not been entirely satisfactory means for accurately measuring the point by point characteristics of an electrodeless discharge plasma. Techniques involving the insertion of probes into the plasma have been found to undesirably disturb the plasma properties. It has been suggested, heretofore, to estimate the plasma profile using a free space microwave propagation technique. However, this type of measurement is both complex and expensive. For example, carefully matched and focused transmitting and receiving antennas and associated microwave interferometric circuits are required in such measurements. Such systems require a considerable number of expensive devices. Further, to determine plasma profiles it is necessary to employ several different bands of microwave equipment and to employ relatively complex analyses which use the data measured in each frequency band to approximately determine the plasma profile. This is costly since each frequency band requires a considerable expenditure in equipment, particularly for the millimeter wavelengths which are required for analysis of dense plasmas. Finally, the free space technique appears to have still another basic disadvantage in measuring very dense plasmas; that is, when the resonant plasma frequency associated with the plasma density approaches the probing microwave frequency, the plasma may alter considerably the microwave field configuration thus making the assumed microwave field configuration in the plasma region uncertain. For these reasons, free-space propagation techniques are limited to relatively diffuse plasmas whose resonant frequencies are considerably less than the microwave probing frequency.

By the present invention there is provided a relatively simple microwave technique which overcomes many of the above described limitations. For example, the technique of the present invention permits accurate measure-

2

ments of plasma profile using only a single microwave frequency. Furthermore, the technique does not disturb the plasma and is usable over a very wide range of plasma densities, and is particularly usable in very high density plasma. Finally, the techniques employed are simple and inexpensive, requiring a minimum of equipment.

By means of the novel apparatus of the present invention relatively dense plasmas (10^{12} electrons/cm.³) are created in the form of an electrodeless discharge by means of inductive coupling from a radio frequency (RF) coil. Preferably, the radio frequency coil is supplied with 40 megacycle power to ionize a low pressure gas, for example, argon in an enclosing envelope. Since the plasma approximates a short-circuited transformer secondary, relatively intense high density plasmas may be generated with moderate RF power and efficient coupling of the RF power to the plasma is achieved. The system of the invention permits X-band (8,840 megacycles/second) waveguide transmission through this plasma without appreciably loading the RF excitation coil or disturbing the plasma properties. By dielectric measurement the point-by-point plasma profile can be measured with a higher degree of accuracy without disturbing the plasma.

Apparatus of this type is useful for re-entry plasma simulation and the investigation of space flight, as well as applications involving power generation and plasma propulsion.

It is therefore an object of the invention to provide novel and improved apparatus for the investigation and measurement of plasma phenomena.

Another object of the invention is to provide novel and improved apparatus for measuring the point-by-point plasma densities with a high degree of accuracy in relatively dense plasmas, using only a single microwave frequency.

It is another object of the invention to provide novel and improved slotted waveguide apparatus for controlled mode plasma diagnostics.

Still another object of the invention is to provide novel and improved apparatus for microwave diagnostic techniques as applied to electrodeless discharge plasmas.

It is yet another object of the invention to provide a novel method, and means therefore, for the measurement of plasma profiles.

These and other objects of the invention will become more apparent upon consideration of the following specification and drawings, in which:

FIGURE 1 is a somewhat diagrammatic illustration of a circular waveguide illustrating the field geometry therein;

FIGURE 2 is a transverse section view of the waveguide of FIGURE 1 and in which a plasma is shown;

FIGURE 3 is a perspective view of a slotted circular waveguide and an energizing helix therefor, useful in the exposition of the invention; and

FIGURE 4 illustrates a preferred embodiment of the invention, wherein the slotted waveguide apparatus is shown in elevation and partially broken away, and in which the ancillary apparatus is shown in block diagram form.

Obviously, the most important characteristic of a microwave diagnostic system is that it be compatible with the techniques used to generate the plasma. This objective is readily achieved by the present invention.

Prior attempts to investigate plasma phenomena have involved the use of the interferometer method in which

3

the contained plasma is placed between the transmitting and receiving horns of a microwave system. However, the cutoff effect defeats the objectives of this method, particularly at high densities. The cutoff effect occurs when:

$$\frac{\omega_p}{\omega} \sim 1 \quad (1)$$

where:

ω_p = resonant frequency of plasma
 ω = microwave frequency.

At low plasma densities the reflections from the tube containing the plasma may overwhelm the small plasma microwave transmission effects. Container reflections generally become predominant when:

$$\frac{\omega_p}{\omega} \angle 10^{-2} \quad (2)$$

where: 10^{-2} represents a given electron density.

These problems are overcome by the technique and apparatus of the present invention as will become apparent from consideration of the following specification. Prior waveguide transmission or microwave horn devices are either noncompatible with RF coil plasma generators or do not have controlled mode propagation in the plasma region. In the present invention, a controlled mode propagation is provided in the plasma region. Also, the apparatus is compatible with RF coil plasma generators and allows microwave probes to sample the microwave power in the plasma region. Another advantage of the invention is an unusually high power transmission capability.

Typically, the apparatus comprises an RF exciting coil which is wound around a glass container containing low pressure argon. The coupling generates the plasma in the low pressure region. From the standpoint of microwave propagation, it would be desirable to insert a solid wall waveguide between the RF coil and the plasma bottle. This, of course, would not be practical since it would short the RF coil currents and preclude the generation of a plasma inside the container. This problem is circumvented by the use of the TM_{01} mode of microwave propagation. The letters "TM" refer to transverse magnetic, while the subscript "01" designates the particular microwave field configuration. To visualize the voltage and currents corresponding to this mode, reference should be made to FIGURE 1 wherein there is shown circular rings of positive and negative charge spaced apart by one-half wavelength. With such geometry, it is obvious that currents will only flow in the axial direction along waveguide 1 as indicated by arrows 2 and 3, and there will be no circumferential current flow. The flux lines of the concomitant electrical fields are indicated by arrows 4-7. The plasma does not change the field configuration, as can be seen in FIGURE 2. The magnetic fields coexisting with the electrical fields indicated by arrows 4-7 have a circular configuration as indicated by dotted lines 8-10 which are coaxial with the major longitudinal axis of the waveguide 1.

The important feature about this particular microwave mode is that it requires only axial wall current as indicated by arrows 2 and 3 in FIGURE 1. Thus, one can cut a series of narrow axial slots in the waveguide wall and these will essentially have no effect on the microwave propagation. At the same time, these axial slots prevent the RF current from flowing in the waveguide. Thus, the plasma generating system is essentially unaffected by the waveguide structure inserted between the RF coil and the container and, at the same time, essentially solid wall waveguide propagation is achieved through the plasma. This particular geometry also has the advantage that both the waveguide mode as well as the plasma configuration are circularly symmetrical. Because of this symmetry, this structure tends not to excite other waveguide modes. In particular, the slotted waveguide structure will propagate only the transverse magnetic type modes and, if the wave-

4

guide size is chosen appropriately, essentially only the TM_{01} mode can propagate in the structure.

In a practical construction the plasma will be contained within an envelope contained within waveguide 1. There is shown in FIGURE 3 a modification of a circular waveguide 11 in which a plurality of longitudinal slots 12-14 are provided in the waveguide wall. Helix 15 encircles waveguide 11 and is energized from a suitable RF source, as will appear hereinafter, which establishes a plasma phenomena within the waveguide 11. This structure will be described in greater detail in connection with FIGURE 4. Slots 12-13 prevent the circular flow of current in the waveguide wall. The continuity of circular mode currents may be interrupted by a single gap although multiple gaps have other advantages which will appear hereinafter. The symmetry of this structure permits single mode propagation to be achieved even in relatively dense plasmas. It is for this reason that the structure is described as a controlled mode plasma diagnostic technique.

Looking now at FIGURE 4 there is shown a system incorporating a preferred embodiment of the apparatus of the invention. This construction comprises a cylindrical envelope 16 for containing the plasma, and may be fabricated from Pyrex glass, fused quartz, or other similar material. The envelope 16 may be approximately two inches in diameter and is provided with an exhaust conduit 17 which is coupled to vacuum system 18 of any suitable and well-known construction. This system may also be adapted to introduce low-pressure argon or other suitable gas into the envelope 16. Circular waveguide 19 encloses envelope 16 and is fabricated from a suitable metal. Rings 21 and 22 are provided at one end of waveguide 19 and surround the neck portion which couples envelope 16 to exhaust conduit 17. These rings (21-22) terminate waveguide 19 in a short circuit so that a standing wave of microwave energy exists in the microwave plasma envelope 16. Helix 23 surrounds the center portion of waveguide 19 and is fabricated from a suitable highly conductive metal. Helix 23 is connected to an RF generator 24 via leads 25 and 26. Generator 24 provides power of the desired frequency which may, for example, be of the order of 40 megacycles and may have an applied power level of the order of several kilowatts. Circular waveguide 19 is provided with a number of longitudinal slots, three of which are indicated at 25-27. A glowing plasma is generated inside envelope 16 via the slotted waveguide section by means of helix 13. Slots 25-27 prevent the RF field from being shorted. Furthermore, the slotted waveguide section acts like a Faraday cage which eliminates the undesired axial electric field between turns of the helix and permits only the desired magnetic field coupling to the plasma.

The end of waveguide 19 opposite rings 21 and 22 is provided with a suitable waveguide mode transducer 31 which couples circular waveguide 32 to rectangular waveguide 33. Waveguide 32 is an extension of slotted waveguide 19, and permits instrumentation of a type to be described hereinafter, to be coupled to the plasma generator. Mode transducer 31 transforms the circular mode (TM_{01}) of waveguide 32 to a rectangular mode (TE_{10}) which is generally more convenient for use with standard microwave test equipment. It should be understood, however, that such mode conversion is merely for convenience and is not a required feature of the invention. Rectangular waveguide 33 couples mode transducer 31 to a calibrated attenuator 34. The input of attenuator 34 is connected to rectangular waveguide 35 for transmission of the microwave energy from isolator 36 via waveguide 37 and T-junction 38. Wave meter 39 will indicate the frequency of the output of microwave generator 41. Waveguide 42 couples the output of generator 41 to isolator 36. Junction 38 communicates the output of generator 41 to wave meter 39 and to oscilloscope 43 via line 44 for monitoring the waveform thereof. The apparatus between generator 41 and mode transducer 33 comprises a microwave bridge

of conventional construction and permits a microwave probing frequency to be introduced into the plasma cavity 16.

Microwave energy from the plasma 45 is picked up by a pair of dipole antenna probes 46 and 47 mounted closely adjacent envelope 16 and which extend through one of the slots in waveguide 19. It is not necessary that both probes 46-47 extend through the same slot. Antenna probe 46 is supported by fixture 48 which is relatively stationary, whereas antenna probe 47 is held by fixture 49 which is mounted by means of leadscrew arrangement permitting it to be rectilinearly translated along the longitudinal axis of the slotted waveguide envelope assembly. Fixture 48 is mounted to a stationary frame 51 via support member 52. Servo motor 53 is mounted by means of stationary frame 51 and is in driving relationship with leadscrew 54 which permits antenna fixture 49 to be translated rectilinearly in the direction of double-arrow 55. A micrometer or dial indicator 56 is fixedly mounted to frame 51 via support member 57. The displacement probe 58 of indicator 56 is coupled to antenna fixture 49 whereby the rectilinear displacement of the antenna probe 47 may be indicated in appropriate units of linear measurement.

Antenna probes 46 and 47 may be of any suitable construction, and may, for example, comprise coaxial lines having dipoles at the ends thereof.

The purpose of the fixed reference probe 46 is to insure that precisely the identical plasma conditions are achieved each time the plasma generator apparatus is turned on for a measurement. This is done by adjusting the RF drive current from generator 24 so that a voltage null appears underneath the fixed reference probe 46. By such an arrangement essentially steady-state plasma conditions can be achieved over a series of measurements. The movable probe 47 is used to determine the characteristics of the standing wave in the cavity 16. Measurement resolution is in part determined by the precision of linear measurement achievable with the movable probe 47 and, in a typical construction, may be of the order of 0.0001 inch. From such measurements the propagation characteristics of the plasma-waveguide system are determined. Such characteristics, in turn, define the point-by-point plasma characteristics.

The gap between envelope 16 and the surrounding waveguide 19 has been exaggerated in FIGURE 4 for the purposes of clarity. However, in an actual construction waveguide 19 is fitted snugly over the glass envelope 16 so that there is less than a $\frac{1}{32}$ inch gap between the waveguide wall and the plasma container. Actual test results indicate that this effectively eliminates leakage and essentially all the power is propagated in the plasma filled region.

During operation, a very intense discharge occurs in the region located approximately at the center of helix 23 and such a discharge approximates a short circuited transformer secondary. In such a ring, discharge of the plasma 45 is generally confined to the region of the coil. This is particularly evident in the closed end of envelope 16. It would also be evident on the opposite end (i.e., near rings 21 and 22) were it not for the electric field capacitance discharge that occurs between the helix 23 and the microwave short-circuit termination (21-22). It is also evident that in such a helix structure there be an axial electric field existing between the turns of helix 23. The waveguide 19, which is inserted between the helix 23 and the plasma container (envelope 16), has the further advantage that it acts like a Faraday cage which shields the plasma from this axial field. This results in pure magnetic field excitation of the plasma which considerably simplifies the analysis of the plasma properties. In particular, it permits the determination of the radial plasma distribution.

In general, measurements consist of determining the position of the voltage node with respect to the short position (L), the distance between successive voltage nodes in the plasma region ($\frac{1}{2}\lambda_p$) and in the empty waveguide

region ($\frac{1}{2}\lambda$), and finally, the width of the voltage node (Δx). These are simple well-known dielectric measurement techniques applied to the problem of plasma measurement. These measured quantities define the propagation constant in the empty waveguide and in the plasma field region. In turn, the propagation constant can be related to the characteristics of the plasma. The plasma characteristics are defined by the equivalent dielectric constant of the plasma (K) which is given by the well-known relationship which involves the plasma resonant frequency (ω_p), the microwave probing frequency (ω), and the plasma coefficient frequency (ν). That is:

$$K = 1 - \left(\frac{\omega_p}{\omega} \right)^2 \left[\frac{1 - \nu/j\omega}{1 + (\nu/\omega)^2} \right] \quad (3)$$

where: $(\omega_p/\omega)^2$ is proportional to the electron density.

The relationship between the propagation constant for the TM₀₁ mode (γ), normalized to the plane wave propagation constant is a vacuum (k), and the equivalent dielectric constant for the plasma is given by:

$$(\gamma/k)_{TM_{01}} = jk^{1/2} \sqrt{1 - \left(\frac{\lambda}{2.61a} \right)^2 \left(\frac{1}{k} \right)} \quad (4)$$

where:

k =plane wave propagation constant in a vacuum= $2\pi/\lambda$

λ =wavelength in a vacuum

a =radius of the waveguide expressed in the same units as the wavelength.

A large radius waveguide is preferred so that the term inside the square root sign will be essentially unity for plasmas whose equivalent dielectric constant does not depart appreciably from unity. This corresponds to low density plasmas. The case when one has a high density plasma will be discussed more fully hereinafter. In this case, Equation 4 simplifies so that essentially the following plane wave approximation is left:

$$(\gamma/k)_{TM_{01}} \approx (\gamma/k) \text{ plane wave} \approx jk^{1/2} \approx \gamma/k + j\beta/k \quad (5)$$

where:

γ/k =normalized attenuation constant

β/k =normalized phase constant.

Since extensive curves are available and well-known to those versed in the art, which relate plasma characteristics to plane wave propagation characteristics, the plane wave approximation of Equation 5 considerably simplifies the practical problem of relating the measured data to the characteristics of the plasma.

For low density plasmas the normalized attenuation constant is proportional to the width of the voltage null and is given by:

$$\alpha/k = 1/2 \left(\frac{\Delta x}{L} \right) \left(\frac{\lambda}{\lambda_p} \right) \quad (6)$$

while the normalized phase constant is given simply as the ratio of wavelengths in the empty waveguide and plasma filled waveguide regions; that is,

$$\beta/k = \frac{\lambda}{\lambda_p} \quad (7)$$

Although the relationship for the normalized phase constant is an exact expression which holds even for high loss plasmas, practically speaking, this relationship is generally only useful when there is a distinct standing wave; that is, a low attenuation plasma. These measurement techniques, although simple, have the advantage of relatively high accuracy. For example, the null width method of determining attenuation, which is used extensively in low loss dielectric and waveguide measurements, can accurately determine attenuations as low as 0.01 db and can be used to estimate attenuations down to 0.001 db. This is considerably more accurate than conventional microwave in-

terferometer techniques of the prior art in which the readable accuracies are of the order of 0.1 db. Further, loss measurements with conventional microwave free space propagation techniques are complicated by the reflections that occur from the walls of dielectric container which holds the plasma.

Typically, a high density plasma will exist approximately at the center of the helix 23 and a large attenuation will occur, which is of the order of 20 to 25 db (order of 10 db/cm.). Since the waveguide diameter is typically of the order of 5 cm. (2 inches) a wave propagating transverse to the axis would suffer large attenuation. The term containing the waveguide radius in Equation 4 physically corresponds to a traverse resonance of the electromagnetic waves; that is, in essence, the electromagnetic energy bounces back and forth between the waveguide walls. Normally, this term would predominate in high density plasmas—thus making invalid the plane wave approximation; however, the above high attenuation tends to damp out this transverse wave. Thus, the plane wave approximation holds even for high density plasmas.

The attenuation in the high density plasma is such that reflections from the short circuit termination (21-22) do not appreciably influence the impedance looking into the plasma from the microwave generator 41 side. Thus, the standing wave on the left corresponds to reflections directly from the plasma; while the standing wave on the right corresponds to reflections from the short circuit termination at the end of the waveguide.

With these measured data, the point-by-point plasma density over the entire plasma filled region can be determined. For example, in the regions where a definite standing wave occurs, the plasma density can be determined by measuring the variation in the phase constant, while in the high density, high attenuation plasma region, attenuation data can be used to determine the plasma profile. Finally, there is a third type of information available from such measurements, comprising the impedance or VSWR (voltage standing wave ratio) looking into the plasma from the microwave generator. This can be employed to make still another investigation of the electron density in the high density plasma region.

The above-described measurements relate essentially to steady-state plasmas in which a movable probe is employed to measure the plasma characters via the fixed microwave standing wave existing in the plasma. It will be readily apparent to those skilled in the art, however, that with slight modification the same basic techniques may be applied to transient plasma measurements. For example, such modification may comprise a series of fixed microwave probes and the standing wave may be shifted by means of sawtooth frequency modulation of the microwave probing frequency. This arrangement will permit determination of the plasma characteristics in much the same way as in the above-described steady state measurements.

Also, it should be noted that the plasma configuration may be altered simply by altering the geometry of the RF exciting coil.

Thus, there has been described a novel method and apparatus therefor, for the investigation of microwave plasma phenomena. While there have been shown and described and pointed out the fundamental novel features of the invention as applied to a preferred embodiment, it will be understood that various omissions and substitutions and changes in the form and details of the device illustrated and in its operation may be made by those skilled in the art, without departing from the spirit of the invention; therefore, it is intended that the invention be limited only as indicated by the scope of the following claims.

We claim:

1. Controlled mode plasma diagnostic apparatus, comprising:

- a plasma enclosing envelope;
- a low pressure gas confined within said envelope
- a circular waveguide, excited in the TM_{01} mode, surrounding said envelope and having a plurality of longitudinal slots therein;
- an induction coil encircling at least a portion of said waveguide; and
- a source of radio frequency energy connected to said coil for excitation of said gas to generate a plasma within said envelope.
2. Apparatus as defined in claim 1 having:
 - a transmission waveguide connected to one end of said circular waveguide for coupling said apparatus to ancillary apparatus.
3. Controlled mode plasma diagnostic apparatus as defined in claim 1 having:
 - means for terminating one end of said waveguide in a short circuit, and thereby permit the establishment of a standing wave of microwave energy in said envelope upon excitation of said coil.
4. Controlled mode plasma diagnostic apparatus as defined in claim 1 having:
 - a selectively movable microwave probe extending through a slot in said waveguide for the detection of microwave energy within said waveguide.
5. Controlled mode plasma diagnostic apparatus as defined in claim 1 having:
 - a fixed microwave probe communicating with the interior of said waveguide;
 - a selectively movable microwave probe extending through a slot in said waveguide; and
 - means connected to said probes for the indication of emitted radio frequency energy.
6. Controlled mode plasma diagnostic apparatus as defined in claim 1 having:
 - a transmission waveguide connected to one end of said circular waveguide; and
 - a microwave probing frequency source coupled to said circular waveguide via said transmission waveguide.
7. Controlled mode plasma diagnostic apparatus, comprising:
 - means for establishing a discharge plasma within a TM_{01} mode waveguide cavity; and
 - a selectively movable microwave probe extending into said cavity for detecting microwave energy emitted at selected points therein.
8. Controlled mode plasma diagnostic apparatus, comprising:
 - means for establishing a discharge plasma within a TM_{01} mode waveguide cavity;
 - a fixed microwave probe extending into said cavity for detection of radio frequency energy generated by said plasma at a given reference point; and
 - a selectively movable microwave probe extending into said cavity for detecting radio frequency energy emitted at selected points along the longitudinal axis of said cavity.
9. Plasma diagnostic apparatus comprising
 - a circular waveguide, excited in the TM_{01} mode, having at least one longitudinal discontinuity therein for the suppression of peripheral currents;
 - means for confining a gas within said waveguide;
 - an induction coil encircling at least a portion of said waveguide for inductively coupling radio frequency energy into said gas confining means;
 - a source of radio frequency energy connected to said coil for generating an electrodeless discharge within said gas confining means; and
 - probe means extending through said discontinuity for detecting microwave energy emitted from said plasma at selected points along said waveguide.
10. Plasma diagnostic apparatus as defined in claim 9, having:
 - means for providing a short circuit termination at one end of said waveguide;

means for supplying a microwave probe signal to the other end of said waveguide; and means connected to said probe detecting means for measuring the microwave power emitted from said plasma.

References Cited

UNITED STATES PATENTS

2,691,133	10/1954	Woodward	324—58
3,225,236	12/1965	Meyer	315—111 X
3,264,508	8/1966	Lai et al.	315—111 X
3,265,967	8/1966	Heald	324—58.5

OTHER REFERENCES

- Gray, "Determining Dielectric Constants," Electronic Industries, November 1960.
- Landshoff, Magnetohydrodynamics, 1957 (Referred to as "MHD").
- 5 RAO et al., Proceedings of the IRE, December 1961 ("IRE").
- Roddy et al., Electronics World, February 1961.
- 10 RUDOLPH V. ROLINEC, *Primary Examiner*.
- P. F. WILLE, *Assistant Examiner*.