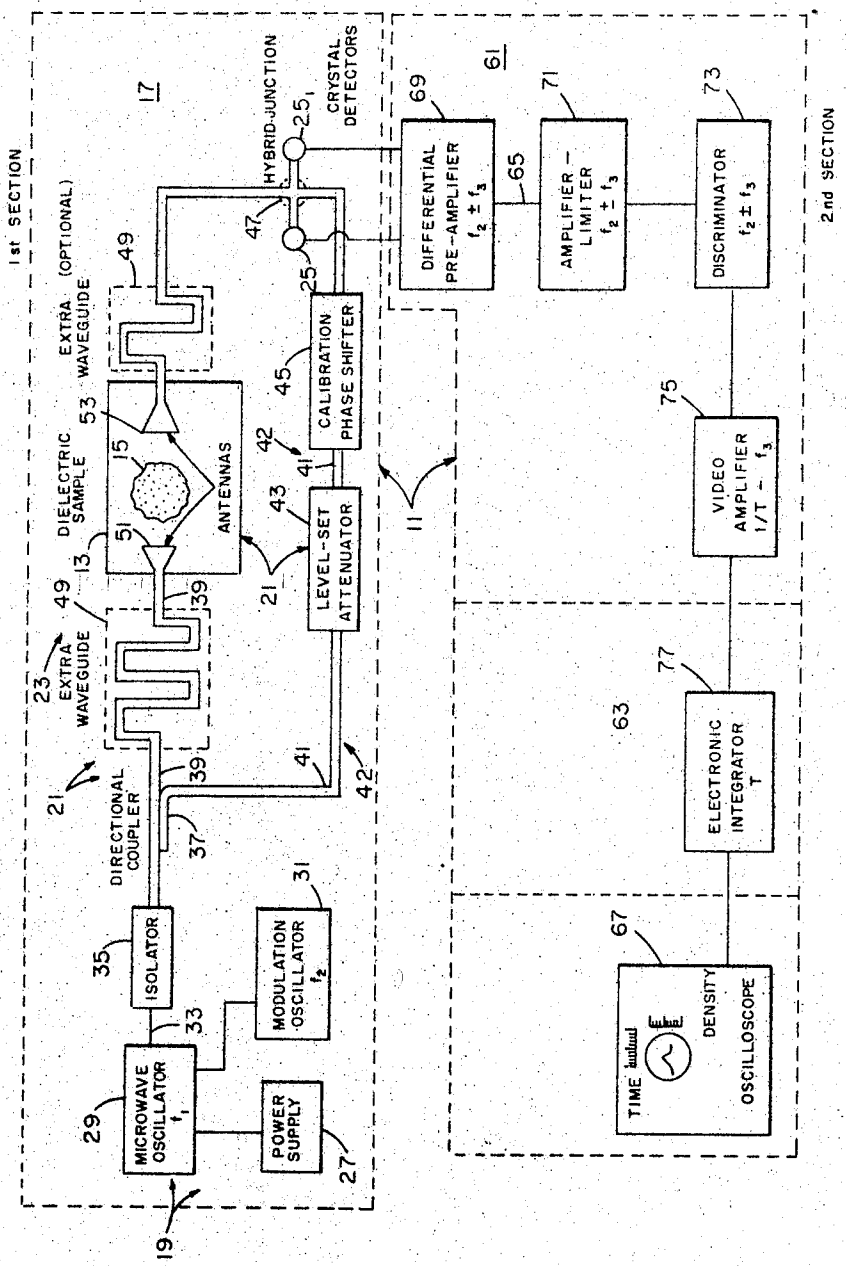
Aug. 9, 1966 M. A. HEALD 3,265,967

MICROWAVE PLASMA DENSITY MEASUREMENT SYSTEM

Original Filed Nov. 16, 1961



INVENTOR.

MARK A. HEALD

BY

Roland A. Anderson

Attorney

United States Patent Office 3,265,967 Patented August 9, 1966

3,265,967

MICROWAVE PLASMA DENSITY MEASUREMENT SYSTEM

Mark A. Heald, Swarthmore, Pa., assignor to the United States of America as represented by the United States Atomic Energy Commission

Continuation of application Ser. No. 153,271, Nov. 16, 1961. This application June 8, 1965, Ser. No. 462,457
3 Claims. (Cl. 324—58.5)

This application is a continuation of application Serial No. 153,271 filed November 16, 1961, now abandoned, entitled "Microwave Plasma Density Measurement System."

This invention relates generally to a microwave measuring system and more particularly to an improved microwave measuring system for determining the density of a plasma of ions and electrons.

In the electronic and atomic energy fields, it has been necessary to produce plasmas of ions and electrons and to measure the plasma characteristics including the plasma density. As described in "Controlled Thermonuclear Reactions" by Glasstone and Lovberg, microwave systems have been advantageously employed for measuring plasma density due to the fact that the probing microwaves have been of such low power that they have caused practically no disturbance of the conditions in the plasma. However, it has been difficult or impossible to provide a microwave system for producing continuous output signal directly proportional to the plasma density below its critical density where the plasma becomes opaque to microwaves.

It has been discovered in accordance with this invention, that these problems are overcome and that a continuous output signal can be provided that varies directly with the plasma density below the critical plasma density, while providing a stable reference signal when the plasma highly attenuates microwaves passing therethrough, by an improved phase detection system. More particularly, this invention in one embodiment contemplates having a frequency modulated signal source having a highly frequency sensitive microwave bridge with crystal detectors for generating a carrier frequency which is phase modulated by the time varying plasma sample in one arm of the bridge, a frequency modulation receiver comprising a differential amplifier, a limiter, a discriminator and a video amplifier connected in a chain to the crystal detectors of the bridge, and an electronic integrating circuit that is operable with the chain seriatim to produce a voltage that varies linearly with the phase modulation of the said signal produced by said detectors. With the proper selection of components and frequencies as described in more detail hereinafter, the desired output and plasma density determinations are provided.

The above and further novel features of the invention will appear more fully from the following detailed description when the same is read in connection with the accompanying drawings. It is to be expressly understood, however, that the drawings are not intended as a definition of the invention but are for the purpose of illustration only.

In the drawings where like parts are marked alike:

FIG. 1 is a block diagram of a preferred circuit in accordance with the present invention for accomplishing plasma density measurements.

Referring now to FIG. 1, measuring circuit **11** measures the density of a plasma, e.g., the free electron concentration of a plasma in container **13**, in accordance with this invention. The plasma container **13** may be a plasma generator such as a Philips Ion Gage, a gas discharge tube, a thermonuclear reactor tube such as is described in U.S. Patent No. 2,910,414 or "Controlled Thermonuclear Reactions" by Glasstone and Lovberg where plasma densities

may be below or above 10^{12} electrons/cm.^{3}, or any other plasma container such as a ballistic tunnel for the study of plasma caused by high velocity projectiles. The plasma in chamber **13** is indicated generally at **15**.

Measurement circuit **11** preferably includes a first section **17** having a frequency modulated signal source **19**, a highly frequency-sensitive microwave bridge **21**, in one arm **23** of which is located the time varying dielectric plasma sample **15**, and microwave detecting means **25**. Frequency modulated signal source **19** includes a suitable power source **27** connected to a conventional klystron or backward-wave oscillator **29** capable of producing microwaves at a frequency f_1 of about 35,000 megacycles per second. A modulation oscillator **31** produces a simple sine-wave intelligence signal of second frequency f_2 of about 30 megacycles per second which frequency modulates the first or carrier waves. A radio-frequency transmission line **33**, commonly referred to as a microwave waveguide, has an appropriate size to deliver the f_1 microwaves through isolator **35** to directional coupler **37** and beyond as will be understood more fully hereinafter. The isolator or padding attenuator **35** prevents any reflected microwave power from altering the frequency or amplitude of the oscillator output as is conventional.

Directional coupler **37** divides the microwave power received from waveguide **33** into a transmission path **39**, and a reference path **41**, comprising bridge arm **42**, a level setting attenuator **43** which adjusts the amplitude of the microwave power passing through path **41** and a calibrated, variable, phase-shifter **45** which in the absence of plasma **15** in container **13** produces with path **39** an interference signal at junction **47** where the two paths **39** and **41** reunite.

Waveguide **49** makes transmission path **39** very much longer than reference path **41** and this transmission path **39** contains suitable directive antennas or horns **51** and **53** between which container **13** holds the time varying dielectric plasma sample whose density is to be measured.

In accordance with the particular system of this invention, it has been found that the plasma phase-modulates the above-described particular microwaves passing through transmission or test path **39** and this phase modulation corresponds to the plasma density. This phase modulation is detected by a balanced mixer comprising crystal detectors **25** which produce a signal at the particular frequency f_2 carrying the phase modulation. This signal is applied to a frequency modulation receiver **61** and an integrating circuit **63** through a coaxial cable **65** and this produces a voltage which varies linearly with the phase-shift produced by the plasma sample **15**. This voltage is fed to an oscilloscope **67** or tape-recorder or other data recording instruments so as to indicate the plasma density directly without complicated calculations and to this end residual amplitude modulation of the microwave oscillator stabilizes the output signal even when the microwaves are highly attenuated by the plasma or the plasma density is high.

The frequency modulation receiver **61** or phase detector **61** of this invention has a differential pre-amplifier **69** that amplifies higher and lower frequencies than the frequency f_2 within a frequency band f_3 determined by the time rate of change of plasma density with the frequency f_2 acting as a center frequency. Coaxial cable **65** transmits the f_2 signal to limiter **71** that removes any amplitude modulation from the f_2 signal, i.e., retains only phase-modulation of the f_2 signal. Discriminator **73** derives variations in the form of a video-frequency voltage in accordance with the frequency modulation of the center frequency f_2. Thereupon, amplifier **75** boosts this video-frequency voltage and transmits it to an electronic time-integrator **77** which recovers the phase modulation envelope produced by the plasma and produces a voltage that is proportional to the

integral of the input signal to the integrator **77**. The integrator has a time constant T long compared with the time $1/f_3$ and an oscilloscope **67** or other recording device displays the integrator output whose voltage directly indicates the density of plasma sample **13**. When the plasma highly attenuates the microwaves passing therethrough or the plasma has a high density, the output signal remains at some constant value characteristics of the apparatus, while again indicating the plasma density at some future time when the plasma becomes transparent.

An example of the parameters of the system of this invention are: f_1=35,000 megacycles per second, f_2=30 megacycles per second, f_3=2 megacycles per second, and T=1 second. In this example, these frequencies must provide $f_1>>f_2>>f_3>>1/T$. Also the degree of frequency modulation, $M=\Delta f/f_1$, of oscillator **29** and the length L of waveguide **49** must be related by the equation M1 approximately equals W where W is the wavelength corresponding to the frequency f_1.

In one embodiment, the crystal detector is a Microwave Associates detector model 1026–AR, the limiter is a 30 mc. I.F. amplifier LEL model I.F. 20B, the discriminator is a 30 mc. ELS model 99, the video amplifier is a Kiethley model 10213 and the integrator is an ELS model 181.

In operation klystron or backward-wave oscillator **29** of frequency f_1, powered by a suitable power supply **27**, is frequency modulated by an oscillator **31** of frequency f_2. The microwave output power of oscillator **29** is delivered to a radio-frequency transmission line such as waveguide **33**. Waveguide **33** if of a size appropriate to the frequency f_1 and is used to interconnect all elements of the circuit operating at the frequency f_1. An isolator or padding attenuator **35** prevents any reflected microwave power from altering the frequency or amplitude of the output of oscillator **29**. The microwave power is divided by a hybrid junction or directional coupler **37** into two waveguide transmission paths **39** and **41**. The power traversing these two paths is later reunited at the hybrid junction **47**. One of these two paths is made very much longer than the other by the inclusion of additional waveguide **49**; the additional waveguide may be located in either path **39** or in path **41**, whichever is more convenient. Path **39** contains a time-varying dielectric sample **15**, the properties of which it is the function of this circuit to measure. Specifically, the sample may be a time-varying ionized gas or plasma. The microwave power is beamed through the sample by means of suitable directive antennas **51** and **53**. The amplitude of microwave power reaching junction **17** by path **41** is adjusted by means of level-setting attenuator **43**. The phase of the microwave signal reaching junction **47** by path **41** is controlled by a calibrated, variable phase shifter **45**, for purposes of calibrating the output signal from the circuit. The output branches of hybrid junction **47** deliver the microwave power to microwave detector crystals **25**, which apply an electrical signal in the vicinity of the modulation frequency f_2 to the differential pre-amplifier **69**. The combination of hybrid junction and detector crystals **25** and 25_1 is sometimes known as a balanced mixer. Time variations of the relative phase of the microwave signals reaching junction **47** by paths **39** and **41**, on account of the action of sample **15** or calibration phase shifter **45**, produce a phase-modulation of the signal at frequency f_2 applied to the pre-amplifier **69**. To preserve this phase-modulation the pre-amplifier must amplify frequencies in the band width f_3 on both sides of the center frequency f_2. The transmission of signals near f_2 between components operating at that frequency is accomplished using flexible coaxial cable **65**. The output of pre-amplifier **69** is delivered to the amplifying and limiting circuit **71**, which removes any amplitude modulation. The output of the limiter **71** is delivered to a discriminator **73**, which provides a video-frequency output in accordance with the frequency-modulation of the signal with center-frequency f_2. This signal is amplified by amplifier **75** and electronically time-integrated by integrator **77** to recover the phase-modulation envelope.

In review of the above Klystron **29** produces microwaves at frequency f_1 and oscillator **31** produces a sine-wave signal at frequency f_2 that modulate the microwaves. Coupler **37** splits the modulated microwaves into two paths. The microwaves in the first or transmission path **39** pass from horn **51** to horn **53**. The microwaves in the second or reference path **41** join with the microwaves from the first path to produce an interference signal at detector **25** that has its principal Fourier component at the harmonic of the modulation frequency nearest to N, where N represents the number of interference cycles arising at the output junction of the dispersive bridge as a result of the frequency excursion of the frequency modulated oscillator (i.e. as a result of the frequency modulation of the microwave oscillators **29** and **31** together with the extra wave guide **49** as observed when the sample **15** is static and transparent to the microwaves). This produces an interference signal having a phase modulation of this principal Fourier component, and this phase modulation of this principal Fourier component is recovered by feeding this interference signal to a tuned amplifier passing only this one harmonic, and feeding this amplifier output seriatim to a discriminator integrator chain. To this end the phase shift caused by plasma **15** in arm **23** produces a phase modulation of this component in accordance with this invention and the phase modulation is recovered by feeding the output signal from the detector **25** to tuned amplifier **69** which passes only this one harmonic and transmitting this harmonic to a discriminator integrator chain wherein the low frequency response is set by the integration time constant. The high frequency response is limited by the carrier-frequency aspect of the (fundamental) modulation frequency.

As will be understood from the above, this invention contemplates the interaction with electromagnetic fields (microwaves) and the measurement of the free electron concentration as a function of the frequency at which this measurement is made. No interference signals which are sinusoidal functions of phase shift are involved in the output. Neither are resonance frequencies, phase-proportional display by means of a raster system or unbalance feedbacks to a frequency modulated oscillator involved.

In contrast to the heretofore known system, where it was impossible to provide a continuous output directly proportional to the plasma density below the critical plasma density and unambiguous when the density is above critical, it is possible with the system of this invention to do this by operation of the described system with a small dispersion such that N is approximately unity and the amplifier is tuned to the fundamental. Thus, the system of this invention has the advantage that it gives direct voltage output and of simple operation at a high modulation frequency.

What is claimed is:

1. A frequency modulated microwave system for measuring the time varying density of a plasma, comprising producing frequency modulated microwaves that are split into a short path and a long path containing said plasma and joined to produce an interference signal carrying a phase modulation corresponding to the phase-shift produced by passing the microwaves through the plasma, said interference signal having its principal Fourier component at the harmonic N of the modulation frequency where N represents the number of interference cycles arising when said split microwaves are joined as a result of the frequency modulation excursion of the microwaves in passing through said plasma, recovering said Fourier component and integrating it to produce a continuous output signal directly corresponding to said plasma density when said plasma is transparent, while indicating unambiguously when the plasma is opaque.

2. The system of claim **1** wherein said modulation is equal to M, said long path is equal to L and ML approxi-

mately equals W where W is the wavelength of said microwaves that are modulated.

3. The system of claim 1 wherein the microwaves have a frequency of 35,000 megacycles per second, the modulation thereof has a frequency of 30 megacycles per second, the time rate of change of the plasma density produces a change in frequencies within a band of frequencies of 2 megacycles per second on either side of said modulation frequency, and said time integration is equal to one second.

References Cited by the Examiner

UNITED STATES PATENTS

2,767,373	10/1956	Maggio	324—57
2,798,197	7/1957	Thurston	324—58.5
2,971,153	2/1961	Wharton et al.	324—58.5

WALTER L. CARLSON, *Primary Examiner.*

A. E. RICHMOND, *Assistant Examiner.*