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OPERATION OF AN ION-CYCLOTRON-WAVE GENERATION APPARATUS IN A RF SELF-SUSTAINED MODE

by Clyde C. Swett, Roman Krawec and Henry J. Hettel

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ABSTRACT

At rf power levels above 19 kw, a hydrogen plasma of average electron density 1 to 2×10^{12} cm^{-3} was produced continuously by an electrostatically-shielded Stix coil. This rf self-sustained mode is possible over a very limited range of magnetic fields ($0.934 \leq \Omega \leq 0.958$, where Ω is the driving frequency divided by the ion-cyclotron frequency), and at a neutral gas pressure of 2.5 microns. Over the range of magnetic fields, the power input to the plasma remains constant for a constant coil current. Magnetic probe measurements indicate a plasma wave having a wavelength approximately equal to that of the rf coil. Some discrepancies between theory and experiment are noted in phases and amplitudes of the probe signals. The wave attenuates rapidly in the uniform field region just outside of the coil, losing most of its amplitude in about one-half wavelength. Probe signals exhibited strong amplitude modulation with components in the 10-100 kc range. Some evidence of wave reflections is noted.

INTRODUCTION

A previous investigation (ref. 1) of ion-cyclotron-wave generation was conducted under experimental conditions whereby ion cyclotron waves were propagated continuously in an axial plasma column generated by a hot-cathode discharge. The d.c. current of the discharge ranged to about 50 amperes. The maximum rf power to the system was 15 kilowatts. Under these conditions trends were observed that indicated the possibility of operation in a self-sustained mode at slightly higher rf power. That is, once the plasma was established and rf power was being absorbed, the hot-cathode could be turned off, the rf both sustaining the plasma and propagating waves. Such operation seemed desirable since it would eliminate many of the problems, such as durability and plasma striations, that arise when using long-duration high-current discharges.

Two other observations were made during that investigation: First, although the rf-peak-power absorption occurred at $\Omega < 1$ (Ω is the ratio of driving frequency to ion cyclotron frequency) indicating generation of ion cyclotron waves, magnetic probes were unable to determine a plasma wavelength and thereby confirm the existence of the waves. The difficulty appeared to result from insufficient distance between the rf coil and the magnetic beach and/or the magnetic mirror. Second, extremely sharp resonances appeared that at times were nonreproducible because of lack of fine control of magnetic field.

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Major modifications were made to the apparatus. The available rf power has been increased to 40 kilowatts, the length of the constant-field section of the magnetic geometry has been doubled, and a precise field control has been installed. Also, in anticipation of greater heat loads, all walls, test section, and other parts have been cooled and a temperature recording system has been installed for making heat balance measurements. These modifications are described briefly herein.

The chief purpose of this report, however, is to present results of a preliminary investigation using this self-sustained mode to study the generation and propagation of ion cyclotron waves.

EXPERIMENTAL APPARATUS

The basic features of the apparatus are shown in figure 1. The apparatus as a whole is designed for continuous operation.

The test section is oriented in a d.c. magnetic-mirror geometry which has a uniformity of approximately ± 1 percent in the region between the mirrors. The current for the coils is supplied by two d.c. generators, the fields of which are energized by a selenium-controlled-rectifier power supply. This power supply is controlled by a signal from a rotating coil gaussmeter, the coil being imbedded in a coil separator near the center of the magnet system. Control of the magnetic field by this method is approximately $\pm 3\times10^{-5}$ tesla. A separate variable power supply connected to two of the magnet coils (beach coils) permits the magnetic beach to be varied between the limits shown (0 to 12 percent beach).

The test section is stainless steel except for two concentric alumina cylinders inside of the rf coils. The nominal size of the stainless steel tubes is 10 cm I.D. These tubes are double-walled so that water can flow axially between them for cooling. Thermocouples are located every 2.5 cm along the tubes in the water passage. A silicone oil flows between the alumina tubes and cools them.

The outer shell of the rf section is stainless steel; its inner surface has been silver plated and gold flashed to reduce the eddy-current heating losses. The rf coil is a four-section Stix coil having four turns per section. The I.D. is 14.2 cm and the wavelength (distance between center of first section and center of third section) is 41.0 cm. The coil was made from 0.95-cm-dia. stainless steel tubing, plated as above, and water cooled. It was fabricated in this manner for better structural support.

An electrostatic shield is located in the oil passage between the alumina cylinders and consists of 25 unplated copper strips 1.27-cm-wide by 0.079-cm-thick spaced 0.16 cm apart. The strips are grounded at both ends to the outer shell by means of radial plates so that the rf coil is completely enclosed by high-conductivity surfaces. The coil-shield combination has a Q of 433 at 6.5 megahertz with no plasma loading.

The initial source of plasma is a hot-cathode discharge produced by an arrangement of heated tungsten wires operated at a potential negative with respect to the metal tube. In the present configuration 18 spiraled wires were used requiring a total heating current of 360 amperes. The discharge current could be varied up to 80 amperes.

Instrumentation available on this apparatus includes magnetic probes, Langmuir probes, hot-wire probes, diamagnetic probe, optical spectometers, microwave interferometer, and a heat-balance measurement system. This latter is a system for determining coolant flow rates and temperatures. The present report is concerned primarily with wave generation; only the magnetic probe system will be described in detail.

Magnetic-probe measurements have been made in two ways: (1) a radial traverse at one of the access ports nearest to the rf coil and (2) an axial traverse by means of a water-cooled probe located near the bottom of the metal tube. The axial probing region is shown in figure 1.

The probes were either 20-turn or 40-turn two layer coils having an I.D. of 0.13 cm enclosed in Vycor glass. The radial traversing probes were moved by a hydraulic system and the axial traversing probes were moved manually.

Measurement of the probe output voltages and their phase with respect to the rf coil voltage was accomplished as shown in figure 2. Coil voltage was reduced and applied to a phase shifter so that the initial phase could be set to zero or any other value desired. The phase and amplitudes of the coil voltage and probe voltage could then be measured either by means of the oscilloscope or the Hewlett-Packard type 8405A Vector Voltmeter. This latter instrument reads out directly both phase and amplitude; it also has phase and amplitude outputs suitable for X-Y plotters. Hence, as the probe is moved the changes in phase and amplitude are plotted directly.

All of the data obtained herein were taken using hydrogen gas at a pressure of 2.5 millitorr.

RESULTS AND DISCUSSION

The first experimental runs with the modified apparatus were made using a 50-ampere discharge current in order to compare rf power absorption with results previously obtained (ref. 1). A similar conditioning procedure was used. The results are shown in figure 3. The shape of the curve is quite similar to that previously obtained, although the peak power absorption now is found at a somewhat higher value of Ω. Such a shift could be the result of a reduced electron density in the lengthened system.

The 50-ampere discharge current was slightly less than that required for self-sustained operation. Increasing the current to 60 amperes caused sudden changes; the discharge-current voltage dropped, the matching network required retuning, the plasma became more uniform and more red, the rf power increased, and the peak of the curve occurred at higher fields. At this time the discharge current could be reduced to zero with only minor changes noted in the plasma. Generally, the rf power increased somewhat as the current was reduced.

Operation in this self-sustained mode is possible at the present time in the very limited region of magnetic fields shown in figure 3 and at pressures close to 2.5 millitorr. It is believed that the total power of 19 kilowatts is barely sufficient to overcome all of the losses and that higher power would provide a wider operating range. The vacuum capacitors in the matching network presently limit the maximum current to the rf coil to about 200 amperes. This limitation will shortly be eliminated by installation of higher-current rating capacitors.

No extensive program has been undertaken to define the self-sustained plasma completely, but a few facts have been ascertained. The electron density is 1 to 2×10^{-12} cm^{-3} and appreciable atomic oxygen (a few percent) is present. The neutral gas pressure drops from the initial value of 2.5 to 0.15 millitorr when the plasma becomes self-sustaining. The plasma appears to be slightly off the centerline of the system and it is not hollow.

Measurements were made with a magnetic probe to determine an axial wavelength. The results are shown in figure 4. The variation of amplitude and phase with axial distance is shown for a probe that measures the axial component of the wave ($\dot{B}_z$). The amplitude decreases quite rapidly and at a distance of one coil wavelength (41.0 cm) is down to 24 percent of the initial value. The phase angle changes linearly with distance and the slope indicates a plasma wavelength of 52 cm. The abrupt change at a distance of 46 cm simply means that the phase angle has changed through 360 degrees and that the meter has switched back to +180 degrees. Beyond this distance 360 degrees has to be added to phase angle changes. At both ends of the meter switching is somewhat erratic because the probe signal is amplitude modulated.

Modulation of the probe signal is shown in figure 5 which is a single-sweep oscillogram of the coil voltage and the probe signal. Low-frequency (approximately 10-50 kilohertz) modulation is present. Some instances have been noted where the probe signal has almost zero amplitude for very brief periods of time. On a time-average basis the modulation is not so apparent. The continuous-sweep oscillogram shows signals that are quite clean (fig. 6). It is probably because of such signals that results with the oscilloscope agree with those of the vector voltmeter.

The reasons for this modulation are unknown; other experiments of this type (e.g. ref. 2) show low-frequency modulation. In the present program low-frequency fluctuations appear in the electron density.

Finding a plasma wavelength (52 cm) approximating that of the coil wavelength (41 cm) is strong evidence for the propagation of an ion cyclotron wave. According to theory only under certain specific conditions will the wavelengths match exactly. In all probability the proper conditions are not produced with the restricted operating range. Some indication of more-nearly-matched wavelengths has been found at lower fields although operation here was not sufficiently stable to permit precise measurement.

Additional evidence concerning the existence of the ion cyclotron wave may be found in the measurements with the radially-traversing probe. Figure 7 shows amplitude and phase measurements for the azimuthal component ($\dot{B}_\theta$) along a radius. Theoretically, for an axisymmetric wave the amplitude of this component should be zero at the center and have a maximum at some radial distance from the center. The data show a finite amplitude at the center, which could result from the plasma's being off center, from the presence of other waves in the plasma, from effects of the probe on the plasma, or merely from finite size of the probe.

The variation in phase with radial position of the probe also has some unexplained features. The abrupt phase shift near the center is expected--the probe passed slightly beyond center--but the gradual changes do not correspond to any simple model of the wave. Similar discrepancies have been noted with probes measuring the axial and radial components of the wave.

One concludes from the probe results that general features of the ion cyclotron wave are observed but that other waves or possibly reflections are present. In fact some evidence for the presence of a reflection is found in figure 8. Although these data were obtained using the hot-cathode source with a 60-ampere discharge current, similar data have also been obtained with the self-sustained mode. At Z = 26 cm the amplitude passes through a minimum and a large change in phase (about 130 degrees) occurs. This can be explained if one assumes two waves traveling in opposite directions so that a standing wave results. The wavelength on one side of the mode is different from that on the other side as determined from the slopes of the curves. No magnetic beach was present in the above experiment; reflection had to be the result of some other factor. The magnetic mirror or possibly density gradients may have been the cause. The reflection phenomenon is extremely sensitive to the value of magnetic field as shown by comparing data in figure 8 with those of figure 4.

CONCLUSIONS

A number of conclusions have been reached as a result of this program:

1. Operation in the self-sustained mode is possible within a restricted range of operation.

2. The self-sustained mode results in generation of ion cyclotron waves.

3. The initial current discharge apparently plays no important role under conditions wherein the self-sustained mode can exist; this may not be so at much larger currents.

4. The wave amplitude decreases rapidly in the uniform-field region adjacent to the driving coils, probably indicating a strong damping mechanism.

5. Amplitude and phase measurements of the wave show reflections under some conditions.

6. The wave measurements, while frequently consistent with theoretical predictions, reveal details difficult to reconcile with any single axisymmetric wave in the plasma.

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2. W. M. Hooke, P. Avivi, M. Brennan, M. A. Rothman, and T. H. Stix, Nucl. Fusion, Suppl. 2, Pt. 3, 1083 (1962).

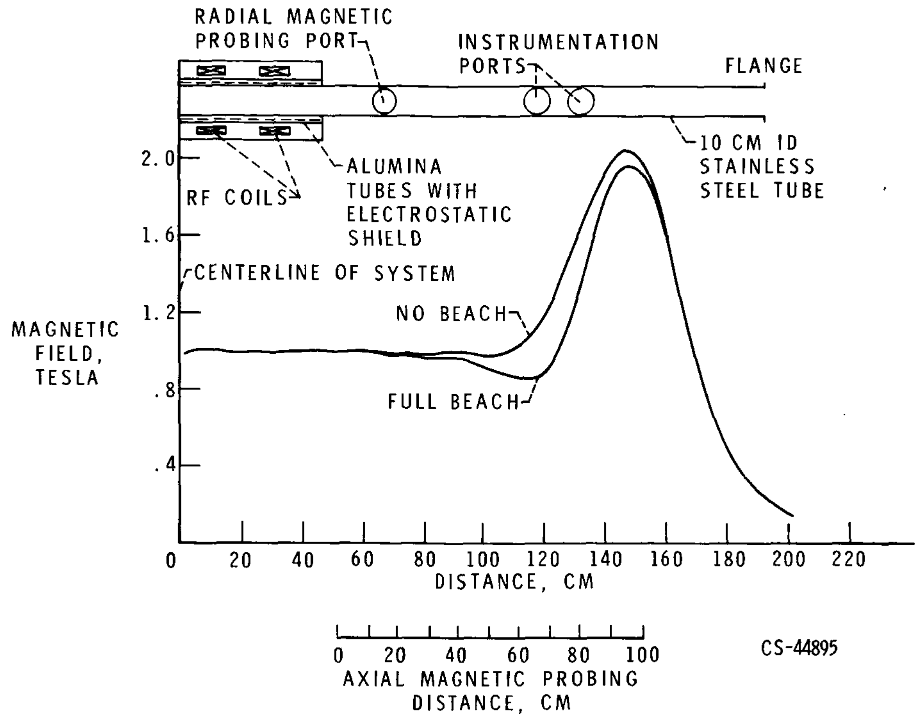

Figure 1. - Magnetic field and vacuum-chamber configuration.

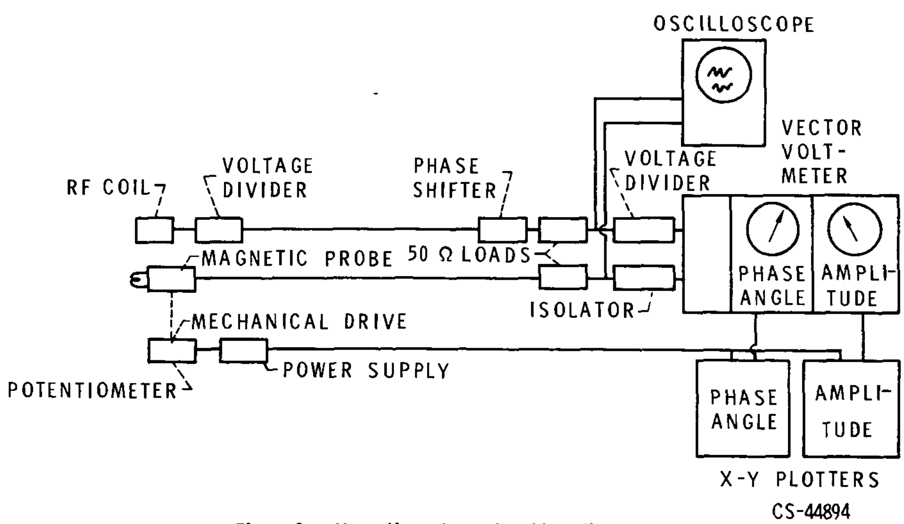

Figure 2. - Magnetic-probe-system block diagram.

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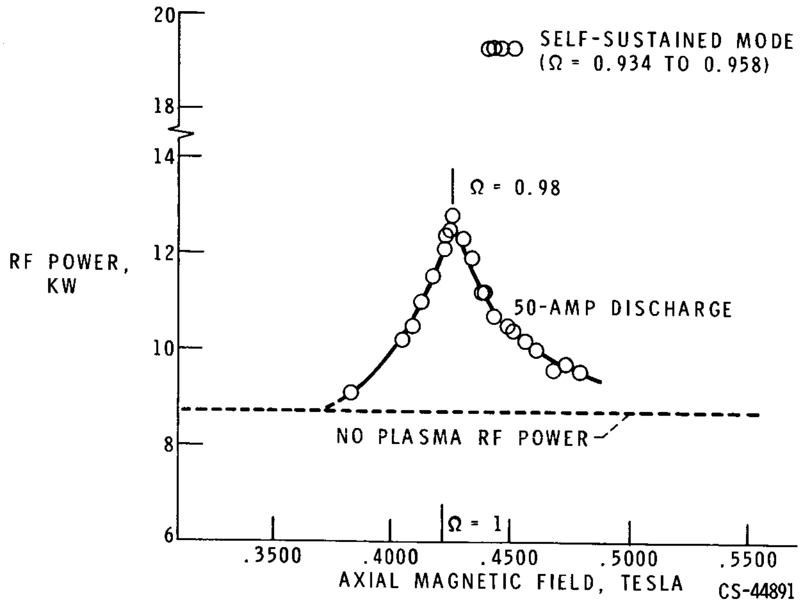

Figure 3. - RF power absorption with the self-sustained mode and with a 50-ampere discharge.

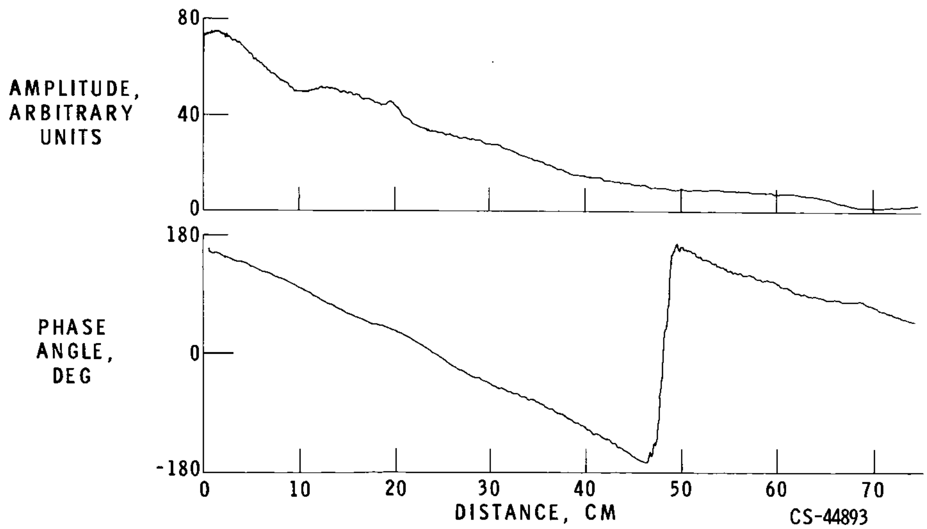

Figure 4. - Typical amplitude and phase measurement-axial tranverse. Bz probe, no beach, RF power 19.8 kW, Ω = 0.945.

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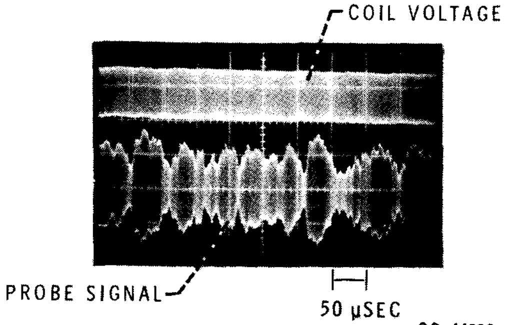

Figure 5. - Single-sweep trace of RF coil and probe voltages.

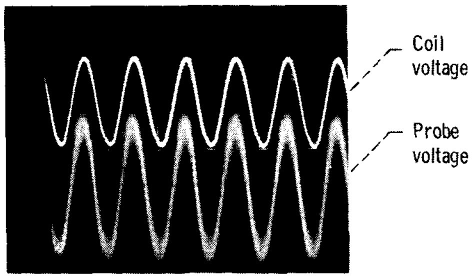

Figure 6. - Continuous-sweep trace of RF coil and probe voltages.

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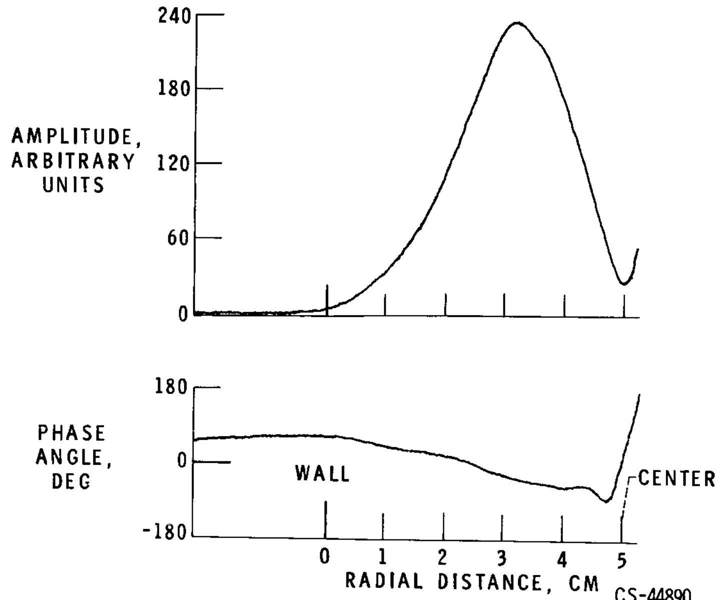

Figure 7. - Typical amplitude and phase measurement - radial tranverse. B_θ probe, no beach, RF power 20 kW, $\Omega = 0.945$.

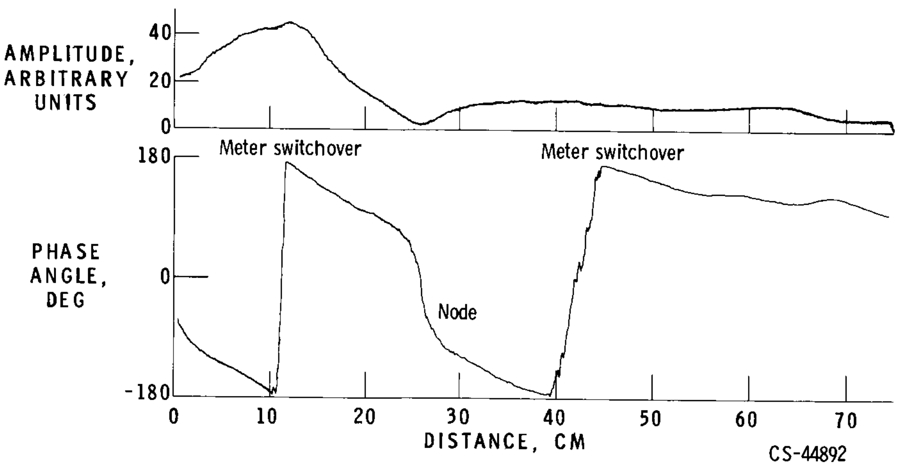

Figure 8. - Amplitude and phase measurement showing evidence of reflection. Bz probe, 60 ampere discharge, no beach, $\Omega = 0.958$.