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OPERATING FEATURES OF AN ION-CYCLOTRON-WAVE PLASMA APPARATUS RUNNING IN THE RF-SUSTAINED MODE

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ABSTRACT

An experimental study has been made of an ion-cyclotron-wave apparatus operated in the rf-sustained mode, i.e., a mode in which the Stix rf coil both propagates the waves and maintains the plasma. Problems associated with this method of operation are presented. Some factors that are important to the coupling of rf power are noted. In general, the wave-propagation and wave-damping data agree with theory. Some irregularities in wave fields are observed. Maximum ion temperature is 870 ev at a density of 5×10^{12} cm^{-3} and rf power of 90 kW. Coupling efficiency is 70 percent.

Introduction

The experimental procedure most widely used in studying propagation and damping of ion cyclotron waves in plasmas has been to create an initial plasma and then apply a pulse of high-frequency current to a Stix rf coil which then generates the waves.[1] Studies of the wave are then conducted at some time during or after the pulse.

One exception to this pulsed procedure is found in the experiments at the NASA Lewis Research Center where the ion-cyclotron-wave phenomena in a steady-state system is being studied. In the initial experiments at this Center, the plasma was generated by a hot-cathode discharge and ion cyclotron waves were coupled into the arc discharge via the Stix coil. Wave studies were then conducted in the plasma that existed for periods of up to 10 minutes. Later experiments showed that as rf power was increased above 15 kW, the hot-cathode discharge became unimportant and could be turned off, whereupon the plasma was sustained by the rf alone. The Stix coil continues to maintain the plasma and launch the waves. This method of operation has been called the rf-sustained mode of operation.

As the program evolved, a number of techniques were developed to surmount certain operating and instrumentation problems. Also, a number of factors that appeared important to the coupling of rf power to the plasma were noted. The purpose of the present report is to discuss some of the problems encountered, their solutions, and some apparatus limitations in operating the rf-sustained plasma at power levels near 120 kW. A more comprehensive discussion of this program can be found elsewhere.[2]

Experimental Equipment

The basic features of the apparatus used are shown in Fig. 1. The apparatus consists of an electrostatically-shielded rf coil (Stix coil) that, in the presence of hydrogen or deuterium plasmas and proper magnetic field, propagates ion cyclotron waves toward two magnetic beach regions. A hot-cathode arc discharge throughout the length of the system is the source of plasma to initiate coupling of the rf power. Other essential parts of the system are corrugated tungsten grid structures (fig. 2) located near the peak magnetic field of the mirror coils. The apparatus as a whole is designed for steady-state (greater than 10 sec) operation.

The apparatus is fully instrumented for rf and heat-balance measurements. Water-cooled probes are used to measure the local rf magnetic field and total $\dot{B}_z$ probes are used for studying the wave fields. Other diagnostics include a diamagnetic-coil system, a neutral particle analyzer, a Langmuir probe system, an optical spectrometer, and a neutron flux survey meter used as a neutron counter.

Equipment Performance and Limitations

The most critical area of the entire apparatus is the rf section. This section has the greatest heat load per unit area and highest rf voltages. The critical elements are the two concentric aluminum oxide tubes located inside the rf coil. They are required to withstand great heat load (inner tube) or high voltage (outer tube).

With the design heat load factor of about 7 W/cm^2 the inner tube was expected to handle about 20 kW. With measured power loss in the rf coil and with experimental facts on plasma heat loss to the tube, the present design should handle a total rf transmitter power of about 45 kW continuously. Actually some fracturing of the tube has been encountered in running at this power for time periods of 3 to 10 minutes. The fractures have been mostly at the ends of the tube and appear to be the result of thermal gradients there. To avoid these fractures, running time was recently limited to one minute for power up to 45 kW and 10 seconds for power above 45 kW with at least one minute between runs. An additional cooled shield on the plasma side of Al_2O_3 tubes could eliminate the heat load problem.

High voltage (up to 60 kV peak) has not been a major problem. Two tubes fractured at the point of greatest electric field--at the center of the system, but these failures were believed to be caused by improper machining that reduced the aluminum oxide tube wall thickness to one half of the specified value.

Probes that are immersed in the rf sustained plasma (density $\approx 5 \times 10^{12}$ cm^{-3}, ion temperature 500-1000 ev, and electron temperature ~ 15 ev) must either be adequately cooled or allowed to remain in the plasma only momentarily. The magnetic probe, total $\dot{B}_z$ probe, and Langmuir probe are in this category. The magnetic probe was in the plasma for long times (few seconds at least); hence it had to be well-cooled. Some conditioning in the plasma was required because of the quartz tube surrounding this probe. It is believed that when this tube was heated to seal the end, the resulting seal was too thick to allow good heat transfer between the plasma and water. The glass surface heated up and eroded rapidly until some equilibrium thickness was reached. Thereafter, the probe had small effect on the plasma, at least at total rf power up to 35 kW. At higher power the probe began to affect the plasma, as observed by reduced plasma loading.

The total $\dot{B}_z$ probe was not in direct contact with the plasma and therefore had negligible effect on power loading. Considerable energy reached the probe via hot neutrals as evidenced by water temperature rise.

Successful use of the Langmuir probe depended on minimal residence time in the plasma. The criterion used for determining this time was that ion saturation current measured as a function of position as the probe was going into the plasma had to be the same as that coming out. By trial and error, the total travel time had to be approximately 0.1 second or less.

Among the most important components in the system are the corrugated tungsten grids. These grids were found to be necessary for satisfactory operation in the rf-sustained mode. Originally, the system was operated without grids using only the arc discharge as the plasma source. Because of the construction of the filament structure and because electrons follow magnetic-field lines, the plasma was very striated. An attempt to break up the striations of the hot cathode arc by introducing grid structures was unsuccessful, but improvement in rf power absorption was striking. Figure 3 shows how the rf power absorption increased and how the maximum power point shifted toward greater magnetic fields indicating increased ion density. With a 50-ampere arc discharge (fig. 3(a)) the resonance is sharp with Ω very close to unity (Ω is the ratio of rf transmitter frequency to ion cyclotron frequency). Over a very narrow magnetic field range (shown by the four points in fig. 3(b)) the arc discharge could be turned off with the plasma being generated by the rf only. Some increase in Ω occurred. When small strip grids (6.0-cm diam) were used, power absorption again improved and further shift in Ω and in operating range was noted (fig. 3(c)). The large strip grid (8.2 cm-diam) again improved performance (fig. 3(c)). Subsequently, a circular grid (fig. 2) was constructed. This grid gave somewhat better power absorption performance than the large strip grid and was easier to fabricate.

Inconsistencies in the position of the power loading peaks were encountered occasionally when grids were changed. It was found that slight tilting of the grid mount was necessary to achieve best power loading. Tilting the grid about 10 degrees from the vertical caused the power peak to shift to higher magnetic fields, indicating higher density. The coupling efficiency also increased. Increasing the angle beyond this value offered no improvement. Supporting the grid in a manner that lengthens the heat flow path also improved performance slightly. The electron density distribution, however, was affected by the tilting, the most uniform distribution being found with extreme tilting--25 degrees--an angle such that an observer looking axially along the system cannot see through the grid. Tilting the grid allows more of the plasma to be intercepted. Visually the grid becomes noticeably hotter and the heating pattern more uniform. All of the experience with grids indicates that the temperature (3000-3200° F) of the grid appears to be an important factor in rf coupling.

A number of experiments were conducted in an attempt to understand the mechanism whereby the grid controls the plasma. The one explanation that appears to agree with all of the facts observed and which appears to be the most likely is that the hot grid dissociates hydrogen and acts as a source for hydrogen atoms. The atoms are free to travel and, in fact, might even be beamed toward the rf coil where ionization by electrons can occur. The axial electric fields under the coil are strong enough to ionize the atoms. In fact, the fields are strong enough to both dissociate the molecules and ionize the atoms but for efficiency it is desired to have only the ionization process.

Wave Propagation, Damping, and Ion Heating

The existence of the ion-cyclotron waves was confirmed by the magnetic probe measurements made throughout the plasma volume. According to theory,[3] the wave component $\dot{B}_z$ is a maximum at the center of the plasma and its phase with respect to some fixed point is constant across the plasma; $\dot{B}_r$ and $\dot{B}_\theta$ are maximum away from the center, zero amplitude at the center, and there is a phase change of 180 degrees upon passing through the center. Axial variations, however, are the same for all components, i.e., any component can be used to determine an axial wavelength.

Measurements of all three components have been made throughout the plasma volume. The $\dot{B}_z$ signal amplitude peaks at the center of the plasma as expected. There is a gradual but definite variation in phase across the plasma, however. The B_θ field is peaked off of the center and is a minimum at the center exactly as expected. Again, the phase does vary between the edge of the plasma and the center of the plasma. Although there is a big change in phase as the probe passes through the center, the phase change is not 180 degrees.

The $\dot{B}_r$ signal instead of being similar to that of $\dot{B}_\theta$ varies almost like $\dot{B}_z$. This may be the result of other radial modes being present or because the rf coil cannot be constructed to give the exact current distribution used in the theory. If the latter is true, some other coil-generated mode, such as the $m = 1$ mode,[4] may be present. What effect these noticeable variations in the wave fields have on the wave damping process is unknown.

Traverses along the plasma column were made with the total $\dot{B}_z$ probe which sums up the $\dot{B}_z$ fields across the plasma. These phase and amplitude measurements show two facts: (1) there appears to be a minimum in the signal amplitude along the axis of the plasma column such as would result from the interference of two waves, and (2) the wavelength as derived from the phase shift is different on each side of the minimum. Locally measured magnetic probe $\dot{B}_z$ signals had considerable amplitude at the same position. The local rf magnetic probe and the total $\dot{B}_z$ probe measurements indicate the complex nature of the wave phenomena.

As the ion cyclotron waves propagate into the decreasing magnetic field of the beach and approach the $\Omega = 1$ point, ion cyclotron damping increases. Wave energy is converted into ion kinetic energy. The probe measurements reveal the general features of wave damping in the beach.

The ion motion should be initially perpendicular to the magnetic field. Because of this perpendicular motion, the ions will be trapped in the small local magnetic mirror. Measurements of the ion temperature in the magnetic beach have been made. The maximum ion temperature is 870 ev with an ion density of 5×10^{12} cm^{-3} and rf power of 90 kW. The peak temperature always occurs at the bottom of the beach.

Other features of the rf-sustained plasma are as follows: The electron density decay time is 850 μsec and the ion energy decay time is 100 μsec--approximately Bohm diffusion time. The electron temperature range is 11-17 ev. Optical spectroscopy indicated that there was approximately 8 percent oxygen in the plasma during the first minute of a run and 16 percent by the third minute and still increasing. Iron and chromium from the stainless steel wall were found at the beach region. Approximately 30-50 percent of the rf plasma power appeared as heat in the aluminum oxide wall at the coil. Increasing the frequency increased the coupling efficiency and the energy density. Many plasma fluctuations were noted, the frequency range being 1 Hz to many MHz.

Conclusions

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

1. Rf power can be coupled with good efficiency (~ 70 percent) to the plasma resulting in ion temperature of about 870 ev and densities of 5×10^{12} cm^{-3} with total rf power of 90 kW.

2. Grid structures are extremely important to the coupling and plasma production process.

3. The critical element for running high rf power (~120 kW) is the aluminum-oxide inner tube. An inner cooled strip shield could eliminate this problem.

4. Wave measurements while generally consistent with theoretical predictions show details difficult to reconcile with any single axisymmetric wave in the plasma.

5. No major differences are found between trends observed with this rf-sustained mode and those observed with the pulse systems.

6. Reproducibility of plasma conditions is quite good even though at the maximum power there are very strong plasma fluctuations that make measurements difficult.

7. Plasma contamination from either the center section or the beach region does not appear to play a strong role in power absorption or wave propagation.

8. This apparatus is considered to be useful for fundamental investigations requiring a reproducible steady-state source of relatively high-density, high-temperature plasma.

[1]W. M. Hooke and M. A. Rothman, Nucl. Fusion 4, 33 (1964).
[2]C. C. Swett and R. R. Woollett, NASA TN (to be published).
[3]D. R. Sigman, NASA TM X-2263 (1971).
[4]D. R. Sigman, NASA TM X-2547 (1972).

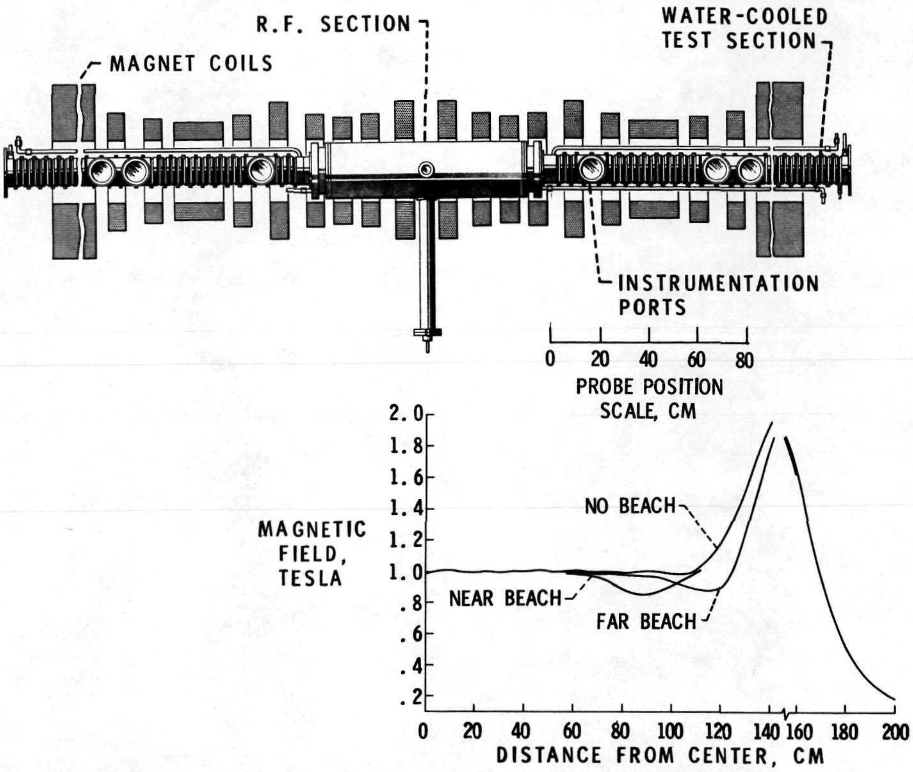

Figure 1. - Magnetic field and vacuum-chamber configuration.

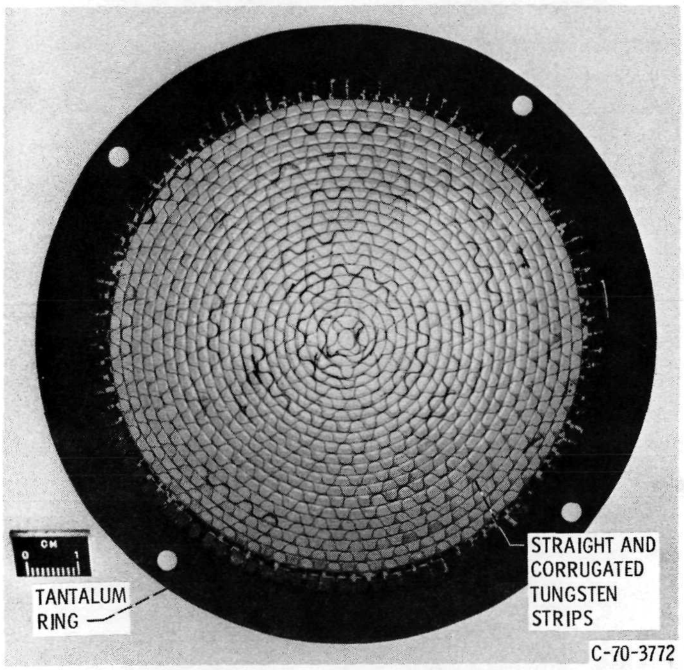

Figure 2. - Circular grid.

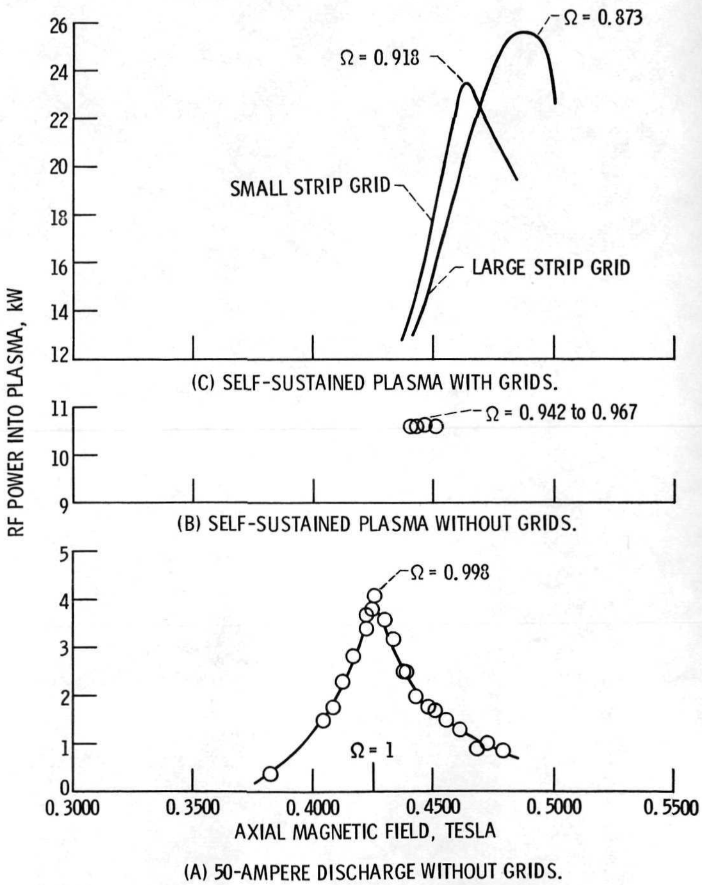

Figure 3. - RF power absorbed by plasma for different methods of operation. Coil current, 200 amperes; no beach, H_2.