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E-3528

EFFECT OF MAGNETIC BEACH ON RF POWER ABSORPTION IN ION CYCLOTRON RESONANCE

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ABSTRACT

Rf power transfer to ion-cyclotron waves in hydrogen and deuterium plasmas was experimentally investigated using a variable magnetic beach inside a magnetic-mirror geometry. The magnetic field at the minimum of the beach could be varied smoothly from 100 to 89 percent of the main axial field. Plasma power absorption at resonance (where the ratio of operating frequency to atomic hydrogen ion-cyclotron frequency, Ω, was 0.94) decreased 45 percent as the magnetic field at the beach was reduced to 89 percent of the main field. The value of Ω at resonance did not change with addition of the beach. A second extremely sharp resonance was noted at a magnetic field corresponding to $\Omega = 0.866$.

INTRODUCTION

A previous investigation (reference 1) has described some experiments on ion-cyclotron-wave generation using an electrostatically-shielded rf coil. Two peaks in rf power absorption using hydrogen were observed in regions near the atomic-ion cyclotron field which were attributed to two wavelengths produced by the rf coil - electrostatic shield configuration. The first peak occurred at $\Omega = 0.968$ (Ω = ratio of operating frequency to ion cyclotron frequency) which corresponds to resonance coupling for the physical wavelength of the rf coil. A second peak at $\Omega = 0.890$ corresponded to resonance coupling for coil wavelength twice that of the actual coil. Fourier analysis of the rf vacuum fields produced by the coil-shield combination indicated strong components for both the actual coil wavelength and for a wavelength twice that value.

One purpose of the present report is to present further results obtained with an improved shielding system. These results include the magnetic-field region in which the second peak was previously observed. The main purpose, however, is to show the effect of adding a variable magnetic beach between the magnetic mirrors of the apparatus. This beach is expected to thermalize the waves (reference 2) and result in ion heating.

EXPERIMENTAL APPARATUS

The apparatus used for the present investigation has been previously described (ref. 1). Figure 1 is a sketch of the basic apparatus. The system as a whole operates steady state.

The test section is oriented in a dc magnetic-mirror field which has a uniformity of $\pm 1\frac{1}{2}$ percent in the region between the mirrors. Two of the dc field coils (beach coils) have been disconnected from the main current supply and reconnected to a separate power supply. The beach coil current can be varied smoothly to change the field strength in the minimum of the beach from 100 to 89 percent of the main field. If the polarity of the supply is reversed, the field at the beach can be reduced to 78 percent of the main field.

The 10-cm-dia. test section is fabricated of stainless steel except for the aluminum oxide tube inside the rf coil. The source of plasma is a hot-cathode discharge produced by an arrangement of tungsten wires operated at a potential negative with respect to the metal tube. Figure 2 shows the filament support structure. There are 10 0.038-cm-dia. filaments connected between the two support rings. The wires are skewed with respect to the cylinder axis as shown. The skewing is such that the magnetic force on the current-carrying wires is inward. The current per filament wire was 15 amperes and the discharge current was 32 amperes. Hydrogen and deuterium were used at an operating pressure of 2 millitorr. Most of the data were obtained with hydrogen except as noted.

Details of the rf coil and electrostatic-shield assembly are shown in figure 3. The water-cooled rf coil is a four-section Stix coil having four turns per section fabricated from 0.95-cm-dia. silver-plated copper tubing. The I.D. of the coil is 13.5 cm and the wavelength (distance between center of first section to center of the third section) is 38 cm. The Q of the coil is 350 at the operating frequency, 6.5 megahertz. The axial vacuum magnetic field of the rf coil is spatially sinusoidal in the axial direction.

The electrostatic shield located on the exterior surface of the aluminum oxide tube consists of 24 1.27-cm wide by 0.079-cm thick unplated copper strips spaced 0.16 cm apart. The strips are held in place by glass tape and are grounded at both ends to the cylindrical enclosure. The return current-carrying surfaces of the stainless steel enclosure are silver plated.

RESULTS AND DISCUSSION

Typical results obtained with the apparatus described are shown in figure 4. The data were taken without a magnetic beach, but are typical of results with beach with certain exceptions to be described later. The rf power absorbed by the plasma at various dc magnetic fields is shown for hydrogen and deuterium. The hydrogen atomic- and molecular-ion-cyclotron fields H^+ and H_2^+, and the deuterium atomic-ion-cyclotron field D^+ are indicated.

Two peaks in power absorption (hydrogen curve) are always observed, one near the atomic- and the other near the molecular-ion-cyclotron field. The peaks in power absorption occur at fields slightly greater than the cyclotron fields indicated. This is in accord with the theory for generation of ion cyclotron waves. The plasma source used generates both atomic and molecular ions. The atomic peak always exhibits a good sharp resonance with good power absorption; in fact it is always difficult to determine the maximum of the peak. The molecular peak exhibits little absorption. Power absorption with deuterium is less than with hydrogen; however, the ion source position and operation were not optimized for these particular data.

The data also indicate that the new electrostatic-shield assembly is quite satisfactory. At fields off the resonance, the power absorption by the plasma drops to about one percent of the total power at the peak. This shield is considerably superior to the shield used in reference 1, which had the single-slot opening too wide, thereby permitting the electrostatic field of the coil to penetrate into the plasma.

Figure 5 compares rf power absorption with and without beach in the region near the atomic cyclotron field. The two major effects to be noted are that the introduction of the beach causes a reduction in power absorption and that the position of the power peak ($\Omega = 0.941$) does not shift significantly.

Why the power absorption should decrease with the addition of a beach is a question that has not been answered. Preliminary tests of the effect of the beach on the plasma column do not indicate that a change in the plasma column is the cause of such power reduction. Hence, it would appear that there is some interaction between the wave and the beach that results in this reduction. Possibly, wave reflections from the beach and/or the mirrors somehow result in a net decrease in power absorption. This conjecture is somewhat substantiated by the fact that probe measurements in the plasma have produced signals that appear to be the resultant of two or more waves.

The fact that the position of the peak does not shift when the beach is used indicates that the ion density remains unchanged. A shift toward higher fields would have indicated increased ion density.

The half widths (expressed as a percentage of the field values at that point) shown on the curves agree reasonably well with theory. However, it has been noted that the half widths are different for each new set of filaments. This variation is probably the result of poor control of final orientation of the filaments due to expansion and inaccurate positioning of the filament structure. Both will cause changes in plasma radius.

During the process of taking the data shown in figure 4 no second peaks were found at $\Omega = 0.890$ such as observed in reference 1. However, when the data were taken using the beach (fig. 5) an extermely sharp resonance was found at .486 tesla ($\Omega = 0.866$). These data could not be reproduced on subsequent days. The control for the magnetic field was not sufficiently fine to permit setting the field to within 0.0035 tesla, which might be responsible for the difficulty in locating so sharp a peak. It is also possible that such a peak was the result of some inhomogeniety of the plasma column which subsequently disappeared. For instance, the plasma column without rf power does visually appear to have striations which diminish or disappear completely when rf power is being absorbed. If such striations result in a plasma with two different density regions then one might expect to observe two peaks. Such peaks may also be present when the beach is not used, but may not be observed until new equipment is installed that will permit controlling the field strength to ±0.0001 tesla.

The final part of this program was to determine how the power changes with insertion of the beach. The rf power changes so rapidly with change in magnetic field that curves such as in figure 5 cannot be easily used to convey the desired information. Therefore, a series of data runs was taken (fig. 6) to show how the rf power varies with beach-coil current at five different settings of the main field. The two upper curves were obtained using fields which produce about maximum power absorption. There is a general reduction in power as the beach is reduced to its minimum value (89 percent of the main field). The decrease in power from full beach-coil current to zero current for the 0.4445-tesla curve is about 45 percent of the rf power going into the plasma.

Points are indicated on the curves where $\Omega = 1$ at the minimum of the beach. Notice that in some regions Ω exceeds unity at the point of minimum field in the beach. Under these conditions, the wave should thermalize or be reflected before it arrives at the minimum of the beach. Hence, the point of thermalization (where $\Omega \approx 1$) shifts toward the rf coil as the minimum in the beach is reduced below the value where $\Omega = 1$. For low power input and, hence, low ion temperature, the wave should not thermalize when $\Omega < 1$ at the minimum of the beach. The reduction of power for any amount of magnetic beach may be due to wave reflections caused by change in impedance that the wave encounters as it propagates into the region of changing magnetic field. The impedance to the wave changes very rapidly as the field is decreased near $\Omega = 1$.

SUMMARY OF RESULTS

The following results were obtained in the experiments to determine the effect of magnetic beach on rf power absorption:

1. The rf power absorbed by the plasma decreased when a magnetic beach was added inside of the magnetic mirrors.
2. A reduction in field strength at the magnetic beach position from 100 to 89 percent caused the rf power absorbed by the plasma to decrease approximately 45 percent.
3. The location of the resonant peak was not changed by the addition of the beach, indicating no increase in ion density.
4. The second resonance previously found at $\Omega = 0.890$ was not observed; however, at $\Omega = 0.866$ a large increase in power was noted when the beach was added, the half width of the resonance being less than 0.0035 tesla.

REFERENCES

1. C. C. Swett, R. Krawec, G. M. Prok and H. J. Hettel, "Experiments on Ion-Cyclotron-Wave Generation Using an Electrostatically-Shielded RF Coil," presented at the American Physical Society Meeting, Washington, D. C., April 26-29 (1965).
2. T. H. Stix, "Generation and Thermalization of Plasma Waves," Phys. Fluids, 1, 308 (1958).

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BASIC APPARATUS

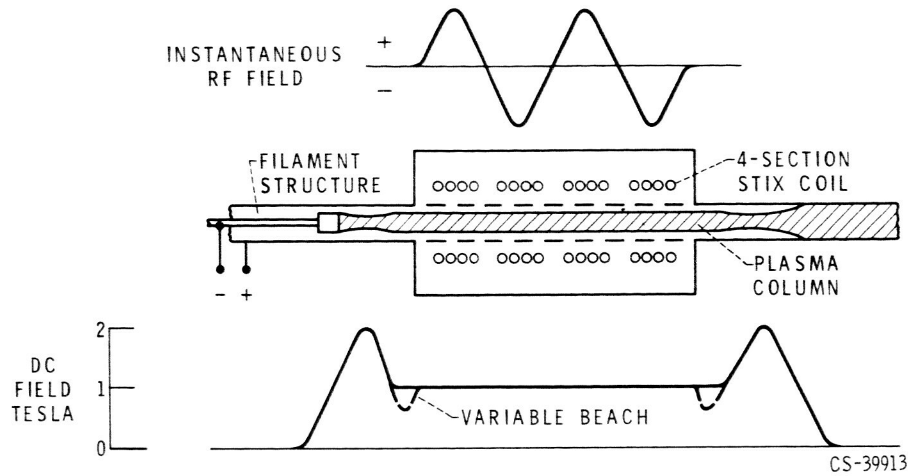

Figure I.

FILAMENT STRUCTURE FOR HOT-CATHODE DISCHARGE

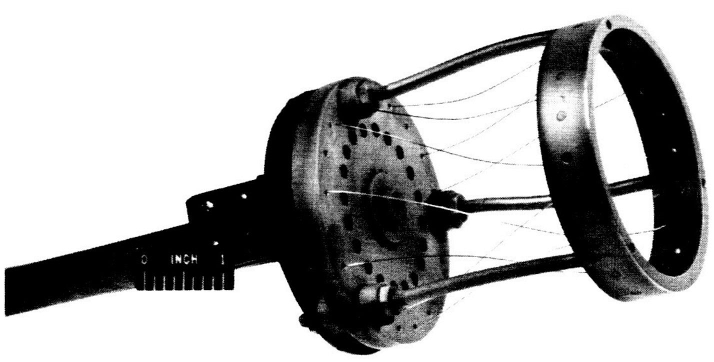

Figure 2.

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COIL-SHIELD ASSEMBLY

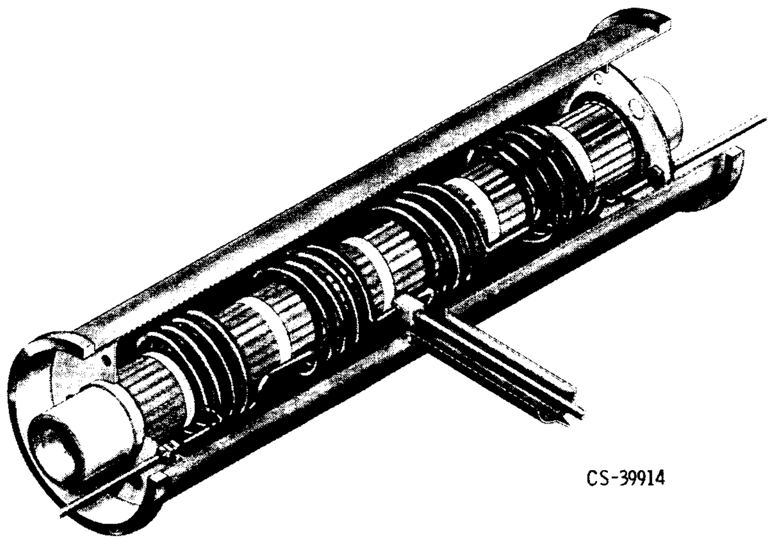

Figure 3.

EFFECT OF MAGNETIC FIELD ON RF POWER ABSORPTION

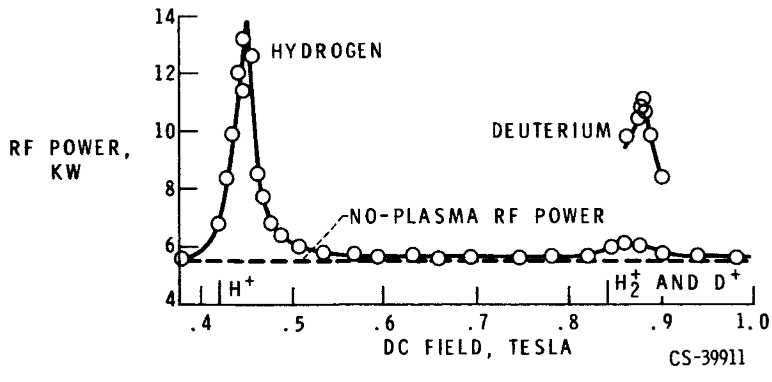

Figure 4.

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EFFECT OF MAGNETIC FIELD ON RF POWER ABSORPTION

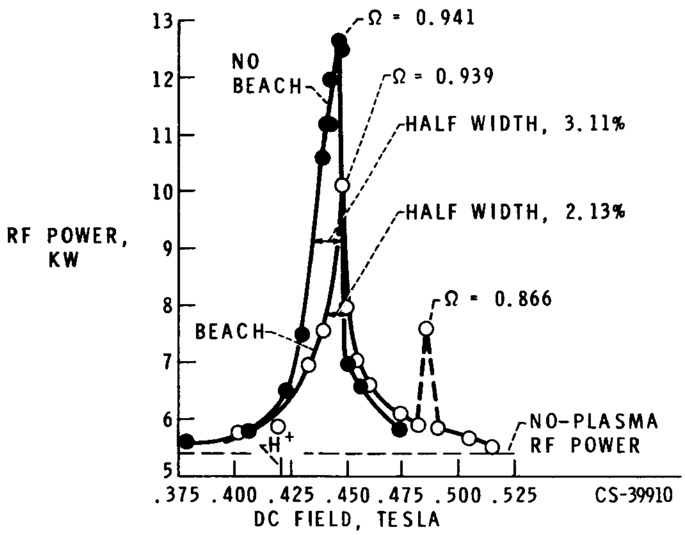

Figure 5.

EFFECT OF BEACH COIL CURRENT ON RF POWER

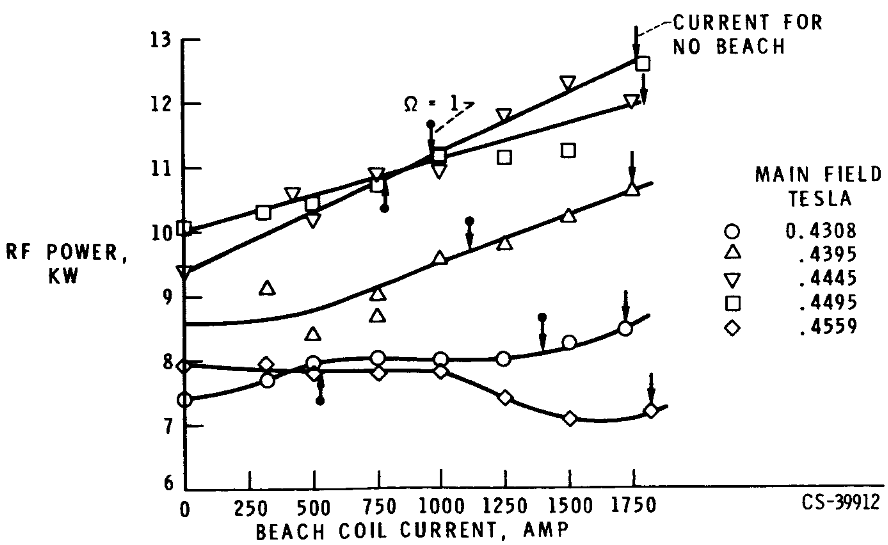

Figure 6.