

FAST MAGNETOSONIC MODES IN THE CALTECH TOKAMAK*

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Fast magnetosonic cavity eigenmodes are being studied in the Caltech tokamak. The toroidal field axis is 4 kG ($f_{ci} = 6$ MHz) and varies by a factor of 2 from the inner to outer wall. The resonant modes have been observed both in transmission and in input resistance measurements. The loop antenna can be matched to the source, either on or off resonance. The resonant input resistance can be up to 1.3Ω , 3 to 4 times the off-resonant resistance. This off-resonance resistance is not much higher than the "vacuum" resistance. The complex input impedance and transmission characteristics are being determined.

A. Introduction

The use of the fast magnetosonic cavity modes as a method to heat plasma has been proposed theoretically for a long time.¹⁻³ Some low and high power experiments have been performed in some of the large tokamaks around the world.^{4,5} As a result of these experiments, some new questions have arisen. We are trying to investigate these eigenmodes in detail at low power, as preparation for future high power heating experiments. Power of 10-300 watts has been used, and frequency range is between 1.2 and 3 times the ion cyclotron frequency.

B. Experimental Setup

The arrangement of the transmitting and receiving antennas is shown in Fig. 1. The transmitting antenna consists of a 2-turn copper loop enclosed in glass. The dimensions of the loop are 6.5×2.5 cm. Because of the small antenna size, its coupling coefficient is very low. Therefore, in order to measure the plasma loading impedance we find it necessary to minimize the antenna resistance. A capacitive matching network, also shown in Fig. 1, is used in order to tune out the antenna inductance and transform the antenna resistance to 50Ω . The transmitting antenna is driven by a 300-watt broad band amplifier. The receiving probe is a 6-turn loop, located 180° toroidally opposite the transmitter.

For plasma loading measurements, a directional coupler is used to obtain the incident and reflected voltages into the antenna system. A r.f. current probe is placed around the antenna to measure the current in the antenna; thus, we can determine the plasma loading resistance using the following equation where R_{ant} is the antenna resistance in vacuum:

$$R = ((P_{inc} - P_{ref})/I^2) - R_{ant} \quad (1)$$

The phase between the incident and reflected voltages has been determined so that the complex reflection coefficient and complex impedance can be calculated.

C. Hydrogen Plasma Parameters

The toroidal magnetic field on axis of the Caltech tokamak is 4 kG (corresponding to $f_{ci} = 6$ MHz); and varies by a factor of two from the inner to outer wall. The electron temperature of the plasma, obtained from Langmuir probe data, is between 50 and 100 eV. Due to pulse discharge cleaning (as proposed by Taylor) the tokamak wall condition is such that the line-averaged

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electron density decays rapidly from $7 \times 10^{12} \text{ cm}^{-3}$ to $1.5 \times 10^{12} \text{ cm}^{-3}$ in the first two milliseconds (Fig. 2). Therefore, most of the eigenmodes appear in the early phase of the tokamak discharge.

D. Transmission Measurements

The first part of the low power experiment is to study the toroidal eigenmodes using the receiving probe. The transmitted signal is very easily observed. Since our transmitting antenna is small compared to the size of the tokamak, various toroidal eigenmodes can be excited. The particular mode excited depends on the input frequency and the plasma density. As the input frequency increases, more eigenmodes can be excited. This effect is shown in Fig. 3, where the peaks in amplitude correspond to the resonances. A given resonance is excited both during the buildup and during the decay of the plasma density.

In Fig. 4 we have plotted the locations of the resonance peaks in frequency vs. density. The figure shows both the theoretical uniform cold cylindrical plasma cutoffs and the experimental data. Assumptions of m_e (electron mass) = 0, and conducting wall boundary conditions are made. One finds the data points fall in the region around the cutoffs, indicating cold plasma theory seems to be valid here.

To further confirm that the peaks in transmission are associated with toroidal modes, we have measured the phase of the received signal with respect to the reference signal. As expected, the peaks in amplitude correspond to a rapid change in phase (Fig. 5).

E. Plasma Loading

In order to efficiently couple r.f. energy into the plasma, it is essential to know the plasma loading resistance. From the measurement of the incident power, the reflected power, and the antenna current, the plasma loading resistance can be determined. Fig. 6 shows a comparison of the transmitted signal with the reflected voltage and antenna current. In this case the antenna is tuned so that during the plasma discharge when there is no toroidal mode present, the antenna is matched to the 50Ω source. When a toroidal resonance occurs the antenna becomes mismatched; therefore, the reflected voltage increases and the r.f. current decreases. We use Eq. 1 to calculate the plasma loading resistance, which is the first trace in Fig. 6. Plasma loading at resonance peaks can be as high as 1.3Ω , which is 3 to 4 times the resistance of the antenna. This is an encouraging result, for it tells us that as much as 75% of the power can be delivered into the plasma, and that only 25% of the power is lost in the antenna.

The phase between the incident and reflected voltage has been measured (Fig. 7). Corresponding to a peak in amplitude, there is a shift in phase, indicating a change in complex reflection coefficient.

F. Resonance Matching

In order to deliver the maximum power into the resonance peaks, it is necessary to match the impedance at a toroidal mode resonance to 50Ω . This process is difficult because both the real and the imaginary parts of the impedance are changing very rapidly. Therefore, it requires some care to transform the resonance loading into 50Ω at the precise point where the real part of the impedance is a maximum and the imaginary part is zero. Fig. 8 shows an example where this has been done.

G. Conclusions

We have observed the toroidal fast-wave eigenmodes in both transmission and antenna loading. The density dependence of the modes agrees satisfactorily with cold plasma theory. Phase variations of the transmitted signal are consistent with the amplitude resonance. Antenna loading resistance at resonance is as high as 1.3Ω . This makes heating using these eigenmodes very encouraging.

References

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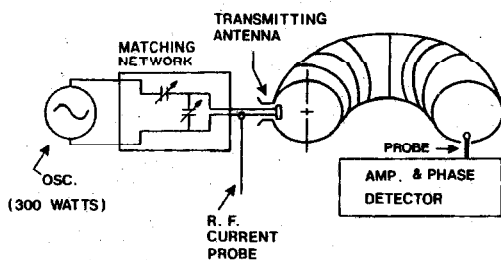


Fig. 1. Schematic of the experimental setup

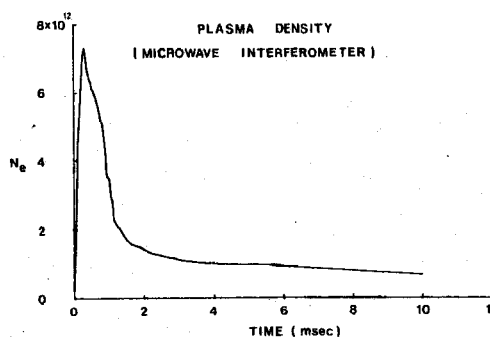


Fig. 2. Electron Density (4 mm microwave interferometer)

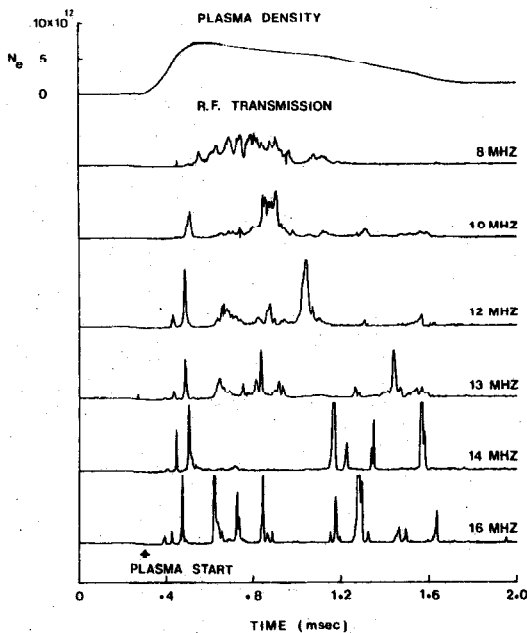


Fig. 3. Transmission Measurements vs. Typical Density Decay

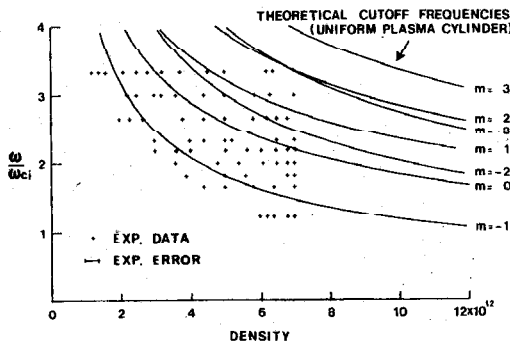


Fig. 4. Theoretical cold plasma cutoffs vs. experimental data

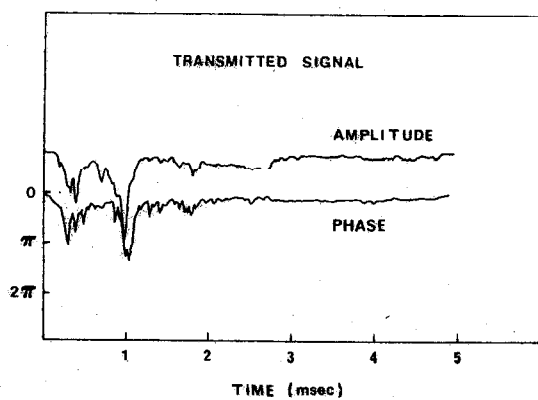


Fig. 5. Phase change of the received signal

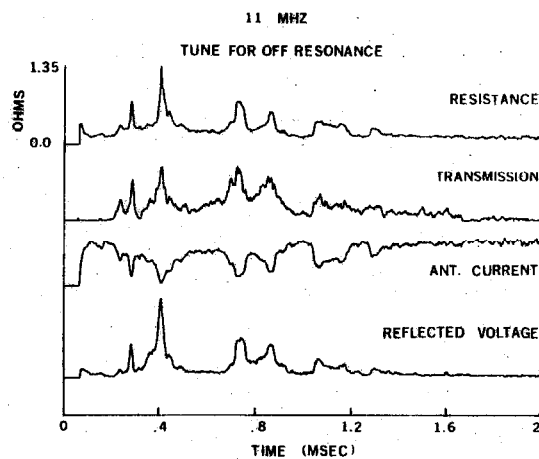


Fig. 6. Calculated plasma loading resistance. Antenna is tuned so that it is matched to 50Ω when no resonance is present.

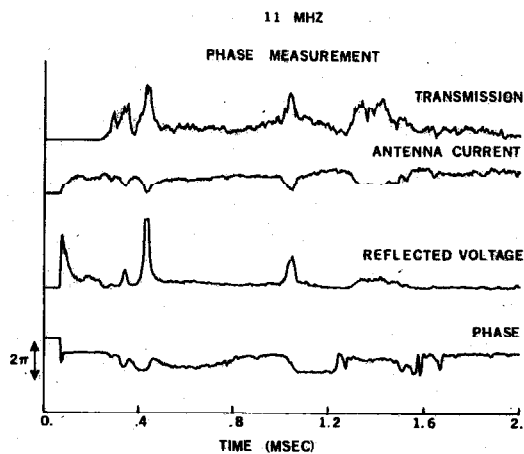


Fig. 7. Phase between incident and reflected voltage

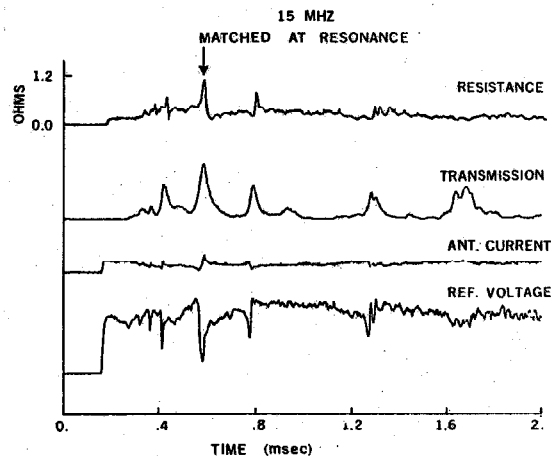


Fig. 8. Antenna is matched to 50Ω at one of the resonance peaks