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Authors

Watson, G
Heidbrink, WW

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Density interferometer using the fast Alfvén wave

George Watson^{a)} and W. W. Heidbrink

University of California, Irvine, 4129 Frederick Reines Hall, Irvine, California 92697-4575

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Utilizing the dependence of the fast Alfvén wave upon density, the mass density evolution of a plasma can be tracked via interferometry. In previous measurements on the DIII-D tokamak [H. Ikezi *et al.*, Phys. Plasmas **3**, 2306 (1996)], fast waves (~ 60 MHz, ~ 5 W) were launched from an antenna at the outer midplane. Detection was hampered by the poor sensitivity of the receiving antennas that were mounted behind protective graphite tiles on the inner wall. New antennas were installed where the graphite tiles were converted to be part of the receiving antenna, increasing reception by at least one order of magnitude. Density evolution measurements with these new antennas (~ 100 MHz, 20 mW) were made for the first several hundred milliseconds until tracking was lost. The plasma shape and an evanescent layer are the main factors for this loss. Changes in wave propagation (as determined by the ray tracing code CURRAY) are less important. When tracking was successful, the density evolution observed from the new antennas show reasonable agreement with existing diagnostics. In addition, by placing receiving antennas on the same wall as the launching antenna and launching a frequency near the ion-ion hybrid frequency, it may be possible to make an ion species mix ratio measurement using the same diagnostic. © 2003 American Institute of Physics. [DOI: 10.1063/1.1527222]

I. INTRODUCTION

In a previous experiment,¹ an ion cyclotron resonance frequency (ICRF) heating antenna was used to launch a 60 MHz, 5 W signal into the plasma. In that experiment, the wave travelled across the torus at the Alfvén speed and was received by small loops mounted behind the protective graphite tile wall of the torus. By using interferometry, monitoring the speed of the wave in comparison to a reference signal, the mass density evolution of the plasma was measured. Because of its potential to provide detailed and inexpensive measurements of plasma density, this ICRF interferometer could prove to be a useful diagnostic. The previous system operated well for limiter plasmas but was unable to perform for diverter plasmas.

The inability to function for nonlimiter plasmas was attributed to the antennae being mounted behind the graphite walls [Fig. 1(a)] of the tokamak. This required the wave to penetrate through the graphite tiles, resulting in significant power loss. The implementation of a new antenna design [Fig. 1(b)] made use of the conductivity of the tiles and also increased the loop area from 3.1 to 7.8 cm².

When a radio frequency (rf) wave, ω , is launched perpendicular to the plasma (Fig. 2) above the ion cyclotron frequency (Ω_{cD}) but below the ion plasma frequency (ω_{pD}), the electron plasma frequency (ω_{pe}), and the electron cyclotron frequency (Ω_{ce}) in the regime of $\Omega_{cD} < \omega < \omega_{pD} \ll \omega_{pe} < \Omega_{ce}$, the launched wave travels at the Alfvén velocity [$V_a = B/(\mu_0 M_D n)$], where B , μ_0 , M_D , and n are the magnetic field, permeability constant, deuteron mass, and ion density, respectively. By comparing the wave speed through the plasma with a reference signal and observing the phase of the

launched signal change, the ion mass density evolution of the plasma can be determined. Since the measured phase (θ) is related to the frequency (f) and the path length (ℓ) by $(2\pi f\ell)/V_a$, the density is

$$n = \frac{(B\theta)^2}{\mu_0 M_D (2\pi f\ell)^2}. \quad (1)$$

Measurement of the phase determines the change in mass density of the plasma, provided that phase tracking occurs. The path length is determined by a ray tracing code such as CURRAY.²

The current design would allow for density evolution measurements while, at the same time, removing the sensitivity to vessel vibrations of a CO₂ laser interferometer. In addition, this diagnostic is sensitive to lower density levels than the existing density diagnostics on DIII-D. Since the phase goes as the square root of the density, this diagnostic can cover a wide range of densities without requiring a high sampling rate.

If the frequency was swept in time, both the density magnitude and the density evolution could be monitored. At present, only a single frequency is launched during a shot, resulting in only density evolution measurements. An initial density measurement is needed from another diagnostic to calculate the magnitude.

The equipment for this diagnostic can also be used as a reflectometer to measure the ion species mix³ with two minor adjustments. The first adjustment is mounting a receiving antenna on the same side of the torus as the launching antenna. The second is to change the launch frequency to the ion-ion hybrid cutoff frequency in the cold ion approximation,⁴ for a deuterium hydrogen species mix

^{a)}Electronic mail: watson@uci.edu

FIG. 1. (a) Previous antenna design with the loops mounted behind the graphite tiles. (b) New antenna design uses carbon tiles as part of the antennas.

$$\omega = \omega_{cH} \left[1 - \frac{n_H}{2(n_H + n_D)} \right], \quad (2)$$

where n_H is the hydrogen density ω_{cH} is the hydrogen cyclotron frequency and n_D is the deuterium density. The hydrogen–deuterium relative concentrations can be measured by calculating the time of flight for the wave as it travels from the launching antenna, reflects off the ion–ion hybrid cutoff layer [determined by Eq. (2)], and is picked up by the receiving antenna (Fig. 2). This diagnostic can apply to any ion–ion species mix, providing that the charge to mass ratios of the two species are different.

II. DIAGNOSTICS SETUP

The current system is a heterodyne interferometer with the intermediate frequency designed for 4 MHz (Fig. 3). The launch signal is used primarily at 100 MHz. The 20 mW signal is launched by a larger version of the modified graphite tile antenna (loop area 16.6 cm²) into the plasma. The data signal traverses perpendicular to the magnetic field at the Alfvén speed, and is picked up by the graphite receiving antennas across from the launching antenna. A minimum of 0.05 mW of power needs to be received for the diagnostic to function properly. The minimum power level could be low-

FIG. 2. Illustration showing simple ray paths (refraction neglected) for both the interferometer and reflectometer. Solid curve is last closed magnetic flux surface at 100 ms, where tracking occurred, while dotted curve is last closed magnetic flux surface at 700 ms, where tracking did not occur.

ered, but to keep from overloading the system, a larger dynamic range is used as a precautionary measure.

After mixing the data and reference signals (100 and 104 MHz, respectively), the resulting data and reference signals are 4 MHz. The reference frequency of 4 MHz is split into two signals, one with a 0° phase shift and the other with a 90° phase shift. These two phase-shifted signals are then separately mixed with the 4 MHz data signal to yield X and Y phase coordinates. When the X and Y components are plotted, the resulting clockwise or counterclockwise loops correspond to an increase or decrease in plasma mass density.

To monitor the amount of power that couples to the plasma, a loading diagnostic is installed. Two input signals are sent to the network analyzer. One signal is the amount of power sent to the launching antenna from the amplifier while the other is the signal reflected back from the launching antenna. The output of the diagnostic is the ratio of the reflected power to sent power. By measuring the magnitude of the power sent to the launching antenna before plasma operations, the magnitude of the signal that coupled to the plasma is known throughout the course of the discharge.

III. RESULTS AND ANALYSIS

The amplitude received from the interferometer (100 MHz) is on the same order of magnitude as the received signal from the previous experiment. (Note: A frequency

FIG. 3. Block diagram of interferometry electronics. The interferometer and reflectometer can use the same equipment by changing launch and reference frequencies.

FIG. 4. Phase evolution of the x and y components with an upper null configuration (SHOT 106214). Tracking occurs between the hash marks.

scan was made from 40 to 120 MHz, with the best signal resolution occurring when the launch frequency was 100 MHz.) However, in the current diagnostic, only 20 mW are launched compared with the 5 W launched from the previous one. In addition, the previous experiment only operated for limiter plasmas while the current one works for limiter and diverter plasmas for the first several hundred milliseconds. Although the current diagnostic only differs from the previous diagnostic by having modified graphite tiles and smaller launched power, the effectiveness of the new antenna design is over an order of magnitude better than that of the previous design.

Due to tracking loss, the data received for the interferometer only measure phase changes for ~ 200 ms. However, the interferometer does operate over a wide variety of plasma shapes and experiments. Figure 4 shows the raw data of the X and Y components. Where the data describe a sinusoidal behavior is termed tracking. Tracking demonstrates that the interferometer is responding to the change in plasma mass density along the ray path. Plotting the X and Y components while tracking yields phase loops as seen in Fig. 5. These observed loops represent the increase in density over time.

To test the accuracy of the interferometer, a theoretical model was constructed to compare against the observed phase change. To obtain the ray, magnetic field, and density information required to solve for θ in Eq. (1), computer codes CURRAY, EFIT,⁵ and GAPROFILES were used, respectively. CURRAY is a three-dimensional ray tracing code for rf waves with frequencies between the ion cyclotron frequencies and lower hybrid resonance frequencies. It is designed

FIG. 5. Phase plot of the x and y components between 75 and 200 ms for the data in Fig. 7(a) (SHOT 106214). The phase loops correspond to the increase of plasma mass density.

FIG. 6. Comparison of the observed phase change using the Alfvén wave interferometer vs the calculated phase change using existing DIII-D diagnostics. Marks along the dotted line would indicate perfect agreement. The solid line is a least-squares fit. Criteria for data was tracking duration exceeded 25 ms and signal amplitude greater than 7 mV.

for tokamak magnetic geometry. In the regime of this experiment, the cold plasma dispersion relation governs wave propagation. Its output yields the ray path and path length. EFIT is used to calculate the plasma shape and magnetic flux surfaces. GAPROFILES produces a density profile by splining together density measurements from existing DIII-D density diagnostics (i.e., Thomson scattering and CO_2 interferometer). A note of caution is required: The density at the core of the plasma is not well known early in the discharge and could lead to significant errors. To compensate, additional CO_2 interferometry chords that were taken near the core were consulted to provide reasonable density values. Thus, CURRAY, EFIT, and GAPROFILES yield the parameters of ray length (ℓ), magnetic field (B), and density (n), each as a function of position.

To calculate the phase delay due to the Alfvén wave speed at a particular time, the ray path was then broken up into many smaller segments. Each segment is then mapped onto a two-dimensional grid. Using the information obtained via CURRAY, EFIT, and GAPROFILES, each phase contribution of a segment is determined by solving for θ in Eq. (1). This procedure is done twice, once for the initial time (t_1) and again for the ending time (t_2), where the resulting phase difference is directly related to the density change between those two times.

The calculated phase difference correlates well with the measured phase difference (correlation coefficient $r=0.76$). However, the calculated phase difference is only $\leq 70\%$ of the observed phase difference (Fig. 6). There are three main sources of error. First, the density is only $\sim 10^{19} \text{ m}^{-3}$ early in the discharge so the individual errors in the Thomson scattering and CO_2 interferometer measurements are $\sim 20\%$. Second, the Thomson scattering density measurements are only available for $\rho \geq 0.4$, so the central density is uncertain to $\sim 50\%$. Third, the density profile outside the last closed flux surface is not known. Estimates based on the edge

Thomson measurements suggest the scrapeoff-layer plasma accounts for a phase change of ~ 3 rad.

So far, tracking has been observed during the first 300–400 ms of the discharge. Tracking lasts the longest for upper null configurations while lower null configurations yield the earliest tracking loss. When the plasma pulls away from the outer wall, tracking is lost (Fig. 2), demonstrating that tracking occurs best when the distance between the antennas and the plasma is minimized. This gap, from smallest to largest, occurred in limiter plasmas, upper null diverter plasmas, double-null plasmas, and lower single-null plasmas. Noncoincidentally, these configurations corresponded to the order of the longest tracking times. In general, tracking occurred most readily when more power was launched, the distance between the antennas and plasma were minimized, higher frequencies were launched, and ohmic plasmas were present. Tracking was less likely if a diverter configuration was used or when a low scrapeoff-layer density occurred.

These trends are consistent with an experiment⁶ in which the loading of an antenna was measured to see how the plasma coupled to different plasmas shapes. The trends found here are consistent with that experiment, strongly suggesting attenuation in the evanescent layer between the antenna and the plasma as the main reason for the loss of tracking.

IV. DISCUSSION

The minimum power level needed for this diagnostic to function properly is 0.05 mW. Due to the commercialization

at this frequency range (50–120 MHz), a system with a lower minimum power level could be built, but careful analysis of the power reception is required.

The comparison of the observed to calculated phase shifts shows reasonable agreement, but is hampered by a lack of density measurements at the core early in the discharge and the exclusion of the density contributions outside of the last plasma flux surface.

The evanescent layer attenuation is the main factor for loss of tracking. For future designs, this issue needs to be addressed, whether it be by larger launched signal, lower minimum power level, or by some other means. While the diagnostic does function for a limited time, the power coupling issues need to be resolved to have the diagnostic operate throughout the entire shot.

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