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Journal

Review of Scientific Instruments, 75(10)

ISSN

0034-6748

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Publication Date

2004-10-01

DOI

10.1063/1.1788833

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Ion species mix measurements in DIII-D and International Thermonuclear Experimental Reactor using ion-ion hybrid layer reflectometry

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(Presented on 20 April 2004; published 7 October 2004)

A superheterodyne reflectometer can provide a direct and inexpensive measurement of the concentrations of ion species with different charge to mass ratios. The ion-ion hybrid cutoff frequency is uniquely determined by the cyclotron frequencies and concentrations of the different species. The phase of a ~ 20 MHz wave that travels from a launching antenna on the low-field side of a tokamak, reflects off the cutoff layer, then travels to a receiving antenna provides a direct measure of the species mix. Hydrogen concentrations between 3% and 67% are measured in DIII-D using this technique. In theory, the technique can measure the spatial profile of the tritium concentration in the International Thermonuclear Experimental Reactor. Possible practical difficulties include attenuation of the wave in the evanescent layer near the antenna. © 2004 American Institute of Physics. [DOI: 10.1063/1.1788833]

I. INTRODUCTION

Ion species measurements in a tokamak plasma have several benefits, including maximizing fusion reactions in a burning plasma experiment, controlling the relative concentrations of minority and majority species in ion cyclotron range of frequency (ICRF) experiments, and understanding the physics of particle transport. Techniques to diagnose the ion species mix include mass-resolved neutral particle analysis, measurements of the flux or spectrum of fusion products, and spectroscopic measurements of radiation from atoms in the plasma periphery. Although all of these techniques provide useful information, alternative techniques that provide direct measurements of the species mix inside the plasma are desirable.

Ikezi *et al.*¹ proposed a reflectometer diagnostic that uses an ICRF wave to measure the ion species mix. With proper choice of frequency, this diagnostic can make a time-resolved measurement deep into the plasma. In addition, with the simplicity of design and commercialization in the radio frequency (rf) band, this reflectometer is a low-cost, practical way to make a species mix diagnostic with good temporal resolution. Results from a proof-of-principle experiment on the DIII-D tokamak were recently published.² This article briefly summarizes those results (Sec. II), then considers the prospects for application of this technique in the International Thermonuclear Experimental Reactor (ITER) (Sec. III).

II. DIII-D EXPERIMENT

The basic concept is illustrated in Fig. 1(a); see also Fig. 1 of Ref. 2. A rf wave with an angular frequency ω that falls

between the deuterium and hydrogen cyclotron frequencies (Ω_D and Ω_H) is launched perpendicular to the magnetic field from the low-field side of the torus. In the proof-of-principle experiment, the launching antenna is a modified plasma-facing graphite tile that forms a single-turn, rectangular toroidal loop.³ The wave launched by this antenna propagates through the plasma until it encounters the ion-ion hybrid cutoff layer (which is small compared to a wavelength), then reflects back to a receiving antenna, which is another modified graphite tile. A superheterodyne system³ measures the phase of the wave at the receiving antenna. The position of the cutoff layer depends on the hydrogen concentration f_H as $\omega_{\text{cutoff}} \approx \Omega_H(1 - \frac{1}{2}f_H)$. In addition to f_H , the wave speed depends on the magnetic field B and the plasma mass density, which are inferred from independent measurements of the equilibrium and the electron density n_e . Thus, it is possible to infer the hydrogen concentration from the measured phase.

Figure 2 shows data from one of the discharges that tested this concept. Normally, the main ionic constituents of the plasma are deuterium and fully stripped impurities that also have a charge-to-mass ratio of $A/Z=2$. In this discharge, hydrogen gas is puffed into the discharge beginning at 0.4 s [Fig. 2(b)]. This causes an increase in f_H [Fig. 2(e)], which causes ω_{cutoff} to decrease. As the cutoff layer moves away from the launching antenna, the measured phase steadily increases, passing through several revolutions in the complex plane [Fig. 2(d)]. At 0.5 s, steady deuterium neutral beam injection commences and the hydrogen concentration increases more gradually. The hydrogen gas puff ends at 0.8 ms, so f_H and the reflectometer phase decrease beginning at this time.

Several additional observations confirm this interpretation of the signals.² The hydrogen concentration inferred

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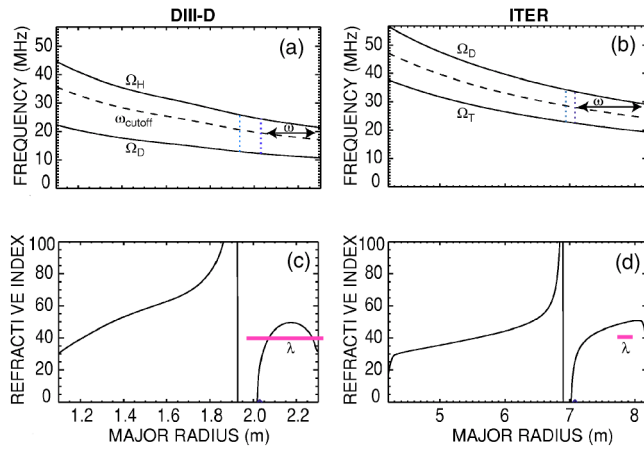


FIG. 1. (Color online) Cyclotron frequencies Ω_i , ion-ion hybrid cutoff frequency ω_{cutoff} (dashed line), and launched frequency ω (line with arrows) vs major radius R in: (a) DIII-D and (b) ITER. The dotted vertical lines show the location of the resonance and cutoff layers, respectively. (Although the curves are labeled by angular frequencies, the ordinate is the frequency in MHz.) Index of refraction n vs major radius in (c) DIII-D and (d) ITER. The gray horizontal lines show the size of one wavelength when $n=40$ in the two devices. For DIII-D, the density and magnetic field profiles are for the discharge shown in Fig. 2 at 0.7 s; a uniform concentration of $f_H=0.4$ is assumed. For ITER, the profiles are from the TRANSP simulation described in Ref. 4; $f_D=0.5$ is assumed.

from these reflectometer measurements agrees quantitatively with the concentration inferred from fusion-reaction and spectroscopic diagnostics within experimental error when the differing spatial sensitivities of the various diagnostics is

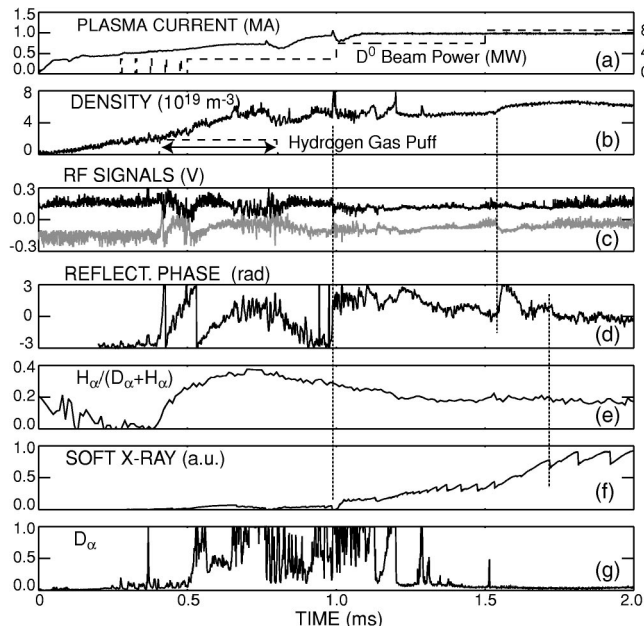


FIG. 2. Time evolution of: (a) plasma current and injected beam power of 80 keV deuterium neutrals, (b) line-average electron density and timing of the hydrogen gas puff, (c) in-phase and quadrature mixed signals of the reflectometer diagnostic, with a dc offset introduced for clarity, (d) the inferred reflectometer phase (after 3.5 ms boxcar smoothing), (e) spectroscopic measurement of the fraction of atomic hydrogen outside the plasma, (f) a central soft x-ray signal, and (g) atomic deuterium and hydrogen light from the inner wall. The vertical lines highlight changes in plasma conditions that cause jumps in reflectometer phase. The phase increases when the cutoff layer moves away from the antennas, which occurs for increasing hydrogen concentration f_H . $B_T=1.9$ T, $\omega/(2\pi)=19.5$ MHz.

taken into account. Raising the launching frequency ω moves the cutoff layer away from the antenna. When waves are launched from the high-field side, the reflected signals are an order of magnitude smaller; this is expected because the waves must tunnel through the ion-ion hybrid resonance (Fig. 1) before they can reflect off the cutoff layer. In contrast to launch from the low-field side, for waves launched from the high-field side, the phase decreases when the hydrogen gas puff commences because an increase in f_H moves the reflecting layer towards the antenna. Taken together, these observations constitute a definitive demonstration that ICRF reflectometry can measure the hydrogen concentration in DIII-D.

In addition to the gross changes in reflectometer phase on a 100 ms timescale, there are also changes in phase associated with plasma instabilities and modifications in edge conditions. Three representative examples are shown in Fig. 2. At a minor disruption (0.985 s), the phase jumps on a millisecond timescale. Smaller rapid jumps frequently occur at a sawtooth crash (1.72 s). Phase shifts on a 10 ms timescale occur in response to an H -mode transition or other changes in edge conditions (1.53 s). Three factors can contribute to these rapid shifts. First, f_H may change: particle transport at instabilities and in different confinement regimes may depend differently on A/Z . (In addition, particle sources may be altered.) Second, the density profile changes, which alters the wave propagation speed. Third, as the attenuation of the primary wave in the scrapeoff-layer plasma changes, the relative importance of parasitic contamination of the received signal by unwanted waves may change, causing a spurious phase shift.

III. APPLICATION ON ITER

Theoretically, extension of this technique to measure the tritium concentration in ITER is straightforward. Figure 1 compares the wave physics in the two devices within the framework of cold-plasma theory. The major-radius dependence of the various frequencies and of the index of refraction n is similar in the two devices. A 28 MHz wave reflects from the cutoff layer at $\omega_{\text{cutoff}}=\Omega_T(1+f_T/2)$ in the plasma interior. In DIII-D, the ray approximation is of dubious validity (although comparisons with a full-wave code indicate it works surprisingly well)² but, in ITER, the wavelength is a smaller fraction of the minor radius, so WKB is a useful approximation. Although ITER is hotter than DIII-D, calculations with warm-plasma theory show that finite beta effects are unimportant on the low-field side of the cutoff layer.² Additional species with other charge-to-mass ratios also have little effect.²

To maximize the D-T fusion reaction rate, it is desirable to match the tritium and deuterium concentrations, $f_T \approx f_D$. The reflectometry technique is useful for a measurement of the tritium concentration but cannot independently determine f_D . All ions with the same charge-to-mass ratio contribute equally to the cutoff frequency, so alpha ash and any fully stripped impurities are indistinguishable from deuterium ions. Independent measurements of the densities of the major impurities or of Z_{eff} are required to determine f_D .

For simplicity, the DIII-D experiments are conducted with a fixed launched frequency ω . In ITER, it is desirable to sweep the launch frequency gradually in time. This enables measurement of the profile of f_T with a single set of antennas. Equally importantly, phase and amplitude offsets associated with changes in plasma conditions in the scrapeoff layer can be detected.

More extensive experiments are needed to assess required edge plasma conditions and rf power levels. The fast wave is evanescent in the low-density region near the antennas. In earlier DIII-D experiments, the same equipment was used at ~ 100 MHz as an interferometer.³ When the plasma was close to the launching and receiving antennas, sensible transmitted signals were detected but, for most plasma conditions, only noise was received. In contrast, the reflectometry system receives sensible signals for all discharges with an appropriate value of ω/Ω_H . It should be noted, however, that the gap between the antenna and the plasma edge is $\lesssim 10$ cm in the studied discharges. In a few discharges, the launched frequency equals the hydrogen cyclotron frequency in the scrapeoff region near the antenna. Phase changes in response to changes in f_H are transient in these cases, perhaps because of cyclotron absorption of the wave energy in the scrapeoff-layer plasma. Reflectometry measurements with high-field side launch are quite sensitive to the plasma

shape. In this case, the received signals are an order of magnitude smaller than with low-field side launch, so losses in the evanescent layer are particularly devastating.

Another important issue for further study is optimization of the launching and receiving antennas. The simple, single-turn loops employed here have a very broad spectrum in wave number \mathbf{k} . Because a broad spectrum of rays is transmitted and accepted, reception of at least some of the power is virtually guaranteed. On the other hand, the power is used inefficiently and it is also possible that unwanted, more complex, ray paths contribute to the signal. If a narrower \mathbf{k} spectrum is employed, multiple receiving antennas should be deployed to ensure reception of the desired bundle of rays.

ACKNOWLEDGMENTS

The authors thank R. Boivin, R. Pinsker, E. Ruskov, and the DIII-D team for their assistance. This work was supported by U.S. DOE Subcontract No. SC-G903402 to U.S. DOE Contract No. DE-DE-FC02-04ER54698.

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