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Experimental Studies of Fast Wave Propagation in DIII-D

H. Ikezi, R.I. Pinsker, S.C. Chiu, and J.S. deGrassie

General Atomics, San Diego, California 92186

Abstract. Fast Alfvén waves radiated from the phased array antenna in the DIII-D tokamak and used for heating and current drive are studied by employing a $\bar{B}$ -loop array mounted on the vacuum vessel wall. The wave propagation direction controlled by the antenna phasing is clearly observed. A small divergence of the rays arising from the anisotropic nature of the fast wave is found. Comparison with a ray tracing code confirms that the ray position calculated by the code is accurate up to at least one toroidal turn of the rays. Conservation of Rk_t which is a basic assumption in computer codes is tested. Although the upshift of toroidal wavenumber k_t at small major radius R is confirmed, Rk_t is not well conserved. A mass density interferometer is demonstrated by employing the extraordinary fast wave.

We have studied experimentally the fast wave propagation in the DIII-D tokamak. The motivation of this work is to find (i) if the wavenumber and if the ray directions are controlled by the antenna phasing in the intended manner and if the ray position predicted by the ray tracing is correct, (ii) if the conservation of toroidal wavenumber, the basic assumption in the computations, is valid, and (iii) if any spurious waves such as surface waves are excited.

DIII-D has three phased array antennas for fast wave radiation [1]. We report the results from the experiments employing one of them. This antenna is on the outboard at the midplane of the vacuum vessel and consists of four current-carrying straps which are separated by 0.24 m toroidally. A boron carbide coated Faraday shield is in front of the antenna straps. The wave frequency is 60 MHz and the ion cyclotron frequency is 7 to 15 MHz.

The wave magnetic field is detected by the $\dot{B}$ -loops which are on both outboard and inboard walls of the vacuum vessel. A pair of loops is on the outboard wall at $\phi = 130$ deg and -130 deg to detect both toroidal and poloidal wave B field. The toroidal angle ϕ is chosen to be 0 deg at the center of the antenna and is positive clockwise from a top view. The loops on the inboard wall are positioned at $\phi = \pm 37.5, \pm 15$, and 0 deg.

The signals from the loops are fed to an interferometer which gives two outputs, c and s , for each loop signal $f(t)$, which are the correlations between $f(t)$ and the reference signals $\cos \omega t$ and the $1/4$ -cycle delayed $\sin \omega t$ which are derived from the master oscillator for the rf transmitter. The angle $\Phi = \tan^{-1}(s/c)$ gives the phase delay during the wave propagation in the plasma $\int \vec{k} \cdot d\vec{r}$ where the integral is taken along the ray connecting the antenna and the $\dot{B}$ -loop.

The phase velocity of the fast wave propagating across the magnetic field equals the Alfvén velocity in our low β plasma. The wave phase shift with respect to the phase in vacuum is measured throughout the discharge. The line-averaged plasma mass density is then obtained. An example is plotted in Fig. 1 (smooth curve). The density from the DIII-D CO₂ laser interferometer is also plotted (noisier curve). Two curves agree with each other well, indicating that the waves launched and detected are fast waves.

Our measurements verify that the ray directivity varies with the phasing at the antenna. An example of ray behavior is shown in the following. The interferometer outputs from two antenna phasing $(0, 0, \pi, \pi)$ and $(0, \pi/2, \pi, -\pi/2)$ are shown in Fig. 2. The inboard loop at $\phi = 0$ receives no single-pass signal indicating that the antenna lobe is directed sideways. The outboard loops at $\phi = \pm 130$ deg receive equal amplitude but opposite sense, when the phasing is $(0, 0, \pi, \pi)$ as we find on the third and fourth traces of Fig. 2(a). Thus the antenna is radiating antisymmetrically.

FIGURE 1. The plasma density obtained by CO₂ interferometer (noisier curve) and by extraordinary fast wave interferometer (quieter curve). $B_t = 2.1$ T, $I_p = 0.8$ MA.

FIGURE 2. The interferometer outputs when the antenna phasings are (a) (0,0, π , π) and (b) (0, $\pi/2$, π , $-\pi/2$).

The fast wave phase velocity is scaled by v_A/c in all directions, so that the phase shift is proportional to $(\text{plasma density})^{1/2}$ in all propagation directions. The estimated phase shift due to the change of density agrees with the observation if one assumes that the ray from the antenna goes directly to the outboard loops.

Switching to current drive phasing (0, $\pi/2$, π , $-\pi/2$) does not alter the signal from $\phi = 130 \text{ deg}$, but the signal from -130 deg is changed entirely as shown in Fig. 2(b). The current driving ray which is going to the positive ϕ is preserved, while the ray going oppositely disappears.

The product of toroidal wavenumber and major radius $k_t R$ is conserved in the toroidally symmetric plasma. The ray tracing [2] and full wave [3] computer codes assume $k_t R = \text{constant}$. We have tested if this assumption is valid.

Figure 3 shows the k_t spectra derived from the inboard probes for three different antenna phasings, (0,0,0,0) in (a), (0, $\pi/2$, π , $-\pi/2$) in (b), and (0, $-\pi/2$, π , $\pi/2$) in (c). We first find that $k_t/2\pi \simeq \pm 2/\text{m}$ for co- and counter current drive phasing. This is k_t on the inboard where major radius R equals 1 m. On the other hand, $k_t/2\pi = \pm 1.04$ is estimated at the position of antenna from the antenna strap separation of 0.24 m. The major radius of antenna position, $R = 2.32 \text{ m}$, gives $R k_t/2\pi = 2.4$ which is somewhat larger than the observed value on the inboard which is about 2, but a clear upshift of k_t at the inboard is found.

There are higher power portions in the spectra of co- and counter current drive phasings. These are the portions where the inboard loop array detects the wave which traveled a single toroidal turn. The lower

FIGURE 3. The wavenumber ($k_t/2\pi$) distributions obtained from three different phasings: (a) $(0,0,0,0)$, (b) $(0,\pi/2,\pi,-\pi/2)$, and (c) $(0,-\pi/2,\pi,\pi/2)$.

power portions are contributed by more than single turn signals. All of our data (several hundred plasma shots) show that k_t is down-shifted and the spectrum is broader after the ray travels a longer distance. In some cases, it is almost one-half the value of a single toroidal turn signal. The $(0,0,0,0)$ phasing introduces the spectra centered near $k_t = 0$. Again, $k_t R$ is not a constant as we find in Fig. 3(a).

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