Radio Frequency Experiments in JFT-2M: Demonstration of Innovative Applications of a Traveling Wave Antenna

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Abstract. Several innovative applications of a traveling wave (combline) antenna designed for fast wave current drive have been demonstrated for the first time in the JFT-2M tokamak. High energy electrons of at least 10 keV were produced in the plasma core by highly directional fast waves in electron-cyclotron-heated plasmas. The ponderomotive potential of the beat wave, produced by fast waves at two different frequencies, was directly measured for the first time by a heavy ion beam probe. Plasma production was demonstrated using the wave fields excited by the combline antenna over a wide range of toroidal magnetic fields (0.5~2.2 T).

1. Introduction

Non-inductive current drive is necessary for steady-state operation of future tokamak reactors. Improved confinement modes can be realized by control of the current profile. Fast wave current drive (FWCD) is an attractive method of non-inductive current drive for tokamak reactors owing to the excellent penetration of the waves to the high temperature plasma core. Direct electron heating by 200 MHz fast waves launched from a phased four-loop antenna array was demonstrated experimentally in the JFT-2M tokamak [1]. Asymmetric phasing of the antenna, necessary to excite unidirectional propagating waves for current drive, caused technical problems of phase control and impedance matching resulting from the mutual coupling between antenna elements. General Atomics (GA) developed a traveling wave antenna (TWA) to maintain good plasma coupling, impedance matching, and array directivity during changing plasma conditions [2]. A combline, a particular type of TWA, was designed and built by GA [3] and installed in JFT-2M in 1996. FWCD experiments using the combline antenna have been carried out as a US-Japan collaboration project.

Theoretical calculations yield the wave field profiles or power absorption profile for estimation of current drive efficiency. Experimental studies of FWCD physics have been performed by measuring the reduction of loop voltage or the driven current profile with the motional Stark effect. More detailed studies of wave coupling, propagation, and absorption require accurate measurements of the electromagnetic field pattern of the fast wave in plasma for comparison with a full wave theory. A new diagnostic method for the direct measurement of spatial pattern of fast wave electromagnetic fields during FWCD is proposed using the ponderomotive potential of low frequency beat waves excited by two frequency fast waves radiated from the combline antenna [4]. The spatial pattern of ponderomotive potential fluctuations in toroidal plasma can be measured with the heavy ion beam probe (HIBP) [5].

Plasma production using conventional loop antennas at normal ICRF frequencies has been studied in TEXTOR-94 [6] and TORE SUPRA [7]. Several applications of this RF

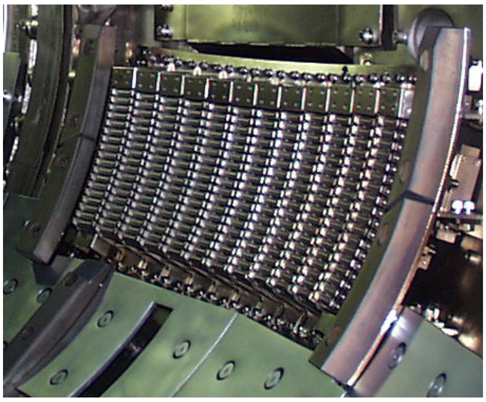

Fig.1 The twelve-element combline antenna array as installed in JFT-2M.

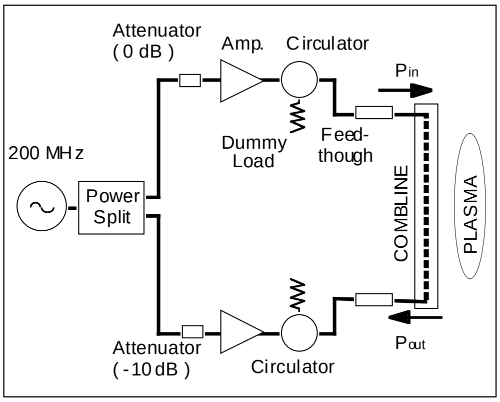

Fig. 2 Schematic of the combline antenna power feed circuit.

produced plasma have been considered: low voltage plasma start-up, wall conditioning, and wall coating. Pre-ionization assisted by the wave fields excited by the combline antenna was tested on JFT-2M taking advantage of the combline's excellent impedance matching properties.

The rest of this paper is organized as follows: Section 2 describes the combline antenna and its RF characteristics. Experimental results are described in Section 3: fast wave current drive experiments are shown in Section 3.1, beat wave excitation and potential profile measurements are shown in Section 3.2, and results from RF plasma production and startup are discussed in Section 3.3. The conclusions are presented in Section 4.

2. Combline antenna

The JFT-2M combline antenna (65 cm in width, 25 cm in height) consists of twelve modules, each of which contains a current strap grounded at one end, open-circuited at the other, a back plate and a three-layer Faraday shield in front and on both sides of the current strap. Figure 1 shows a photograph of the antenna array and the pair of associated limiters as installed in JFT-2M (R/a =1.31 m/0.35 m, $\kappa \le 1.7$, $B_T \le 2.2$ T). The combline antenna power feed circuit is shown in Fig. 2. RF power is applied to one end of the array through a single vacuum feedthrough and the wave energy propagates along the array via mutual reactive coupling between elements. The power not radiated from the antenna emerges from the feedthough at the other end of the array and is absorbed in a dummy load by way of a circulator. The direction of the power propagation can be switched quickly by adjusting the attenuators. The twelve-element array producesa highly directional wave as shown in Fig. 3. The peak parallel index of refraction is $n_{//}$ ~ 5 with $\Delta n_{//}$ ~ 1.6 and ~80 % of the total power radiated in the desired direction. The first high power combline experiments demonstrated good plasma coupling, power handling and excellent impedance matching capability [8]. To date, the combline has not shown any power handling limit up to the maximum power applied to the antenna (400 kW).

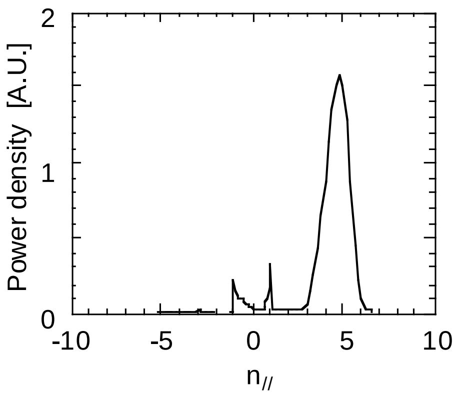

Fig. 3 Calculated $n_{//}$ power spectrum radiated by the combline antenna.

3. Experimental Results

3.1 Fast wave current drive experiment

Fast wave heating and current drive experiments

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have been carried out over a wide range of plasma parameters (n_e=0.2~2.0×10^{19} m^{-3}, B_T=1.0~2.2 T, I_P=0.1~0.2 MA), in upper or lower single-null divertor and D-shaped limiter configurations. Titanium gettering and Taylor type discharges have been used for wall conditioning; boronization has been introduced for more effective wall conditioning in the latest experiments. The fast wave absorption strongly depends on the electron temperature of the target plasma. The plasma was heated by second-harmonic electron cyclotron heating (ECH) at 60 GHz. The typical time behavior of plasma parameters for FWCD experiments are shown in Fig. 4. The heavy lines show a discharge with FW (235 kW) injection into an ECH-preheated plasma, while the lighter lines show the case without FW injection with the same ECH power (215 kW). The central electron temperature (determined from the slope of the soft X-ray energy spectrum in the energy range of 5−10 keV) increased from 2 to 3 keV with FW injection but the temperature begins to decrease 50 ms after FW is applied due to increased density and radiation loss. Power absorption efficiency estimated from time derivative of the plasma stored energy is roughly 50 % both for ECH and FW. Figure 5 shows the energy spectra of the soft X-ray radiation. The radiation emitted parallel to the drift direction of the current-carrying electrons on the midplane was measured with an intrinsic Ge detector. The increase in the 5−10 keV energy range with FW injection indicates that FW accelerates electrons at least up to 10 keV. This result indicates an upshift of $n_{//}$ spectrum to ~7 from the imposed value $n_{//}$=5.

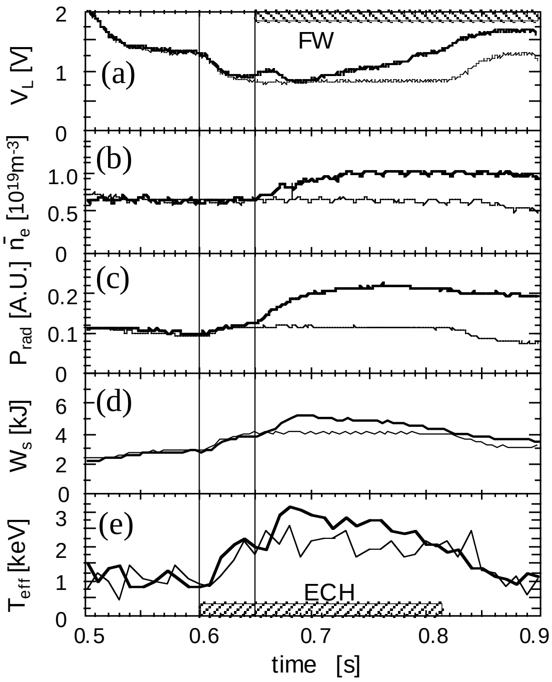

Fig. 4 Time behavior of plasma parameters for a discharge with FW and ECH (heavy lines) and with ECH only (lighter lines).

Code calculations predict a non-inductive current of 60 kA at P_{FW}=400 kW, T_{e0}=2 keV. Detailed comparison between co and counter FWCD has been carried out in a range of electron density $\bar{n}_e$=0.2~2.0×10^{19} m^{-3}. No appreciable differences, however, were observed in surface loop voltage and soft X-ray spectra between the co and counter current drive discharges. Suppression of the density increase during FW injection is needed to make clear the current drive, since T_{eff} decreases within 50 ms after starting FW injection, but longer time scale should be required to detect the difference in the surface loop voltage.

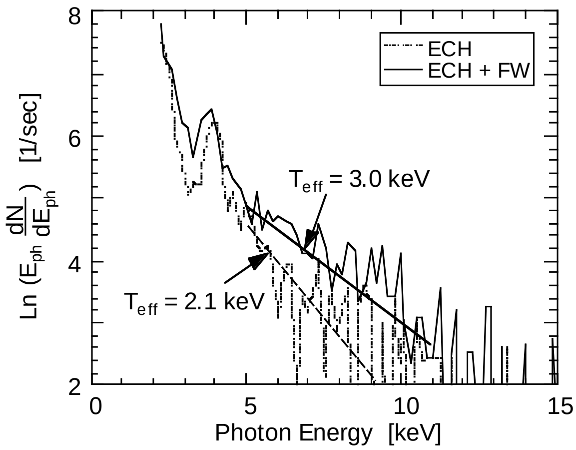

Fig. 5 Soft X-ray energy spectra: B_T= 1.07 T, I_P= 170 kA, $\bar{n}_e$=0.6×10^{19} m^{-3}, P_{ECH}=215 kW and P_{FW} =235 kW.

3.2 Electromagnetic field pattern measurement of fast wave

The combline antenna is a moderate bandwidth device (200 ± 5 MHz). This characteristic enables simultaneous operation of the combline at two frequencies to excite

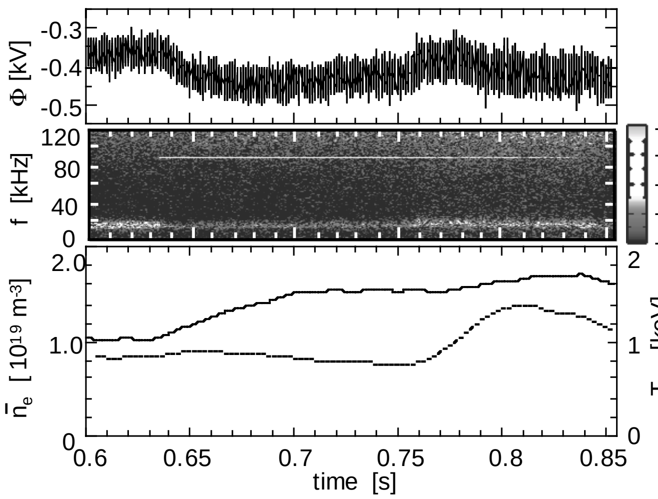

Fig. 6 Time traces of (a) HIBP potential signal, (b) frequency analysis of potential signal, (c) electron density and central electron temperature.

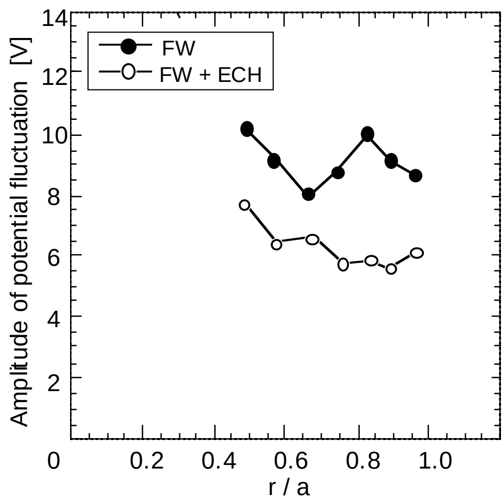

Fig. 7 Beat wave potential profile during FW (t=0.7 s) and FW+ECH (t=0.8 s).

beat waves in the plasma. The HIBP using Tl^+ beam at an acceleration voltage of 350 keV can measure potential fluctuations and density fluctuations with a spatial resolution of 6~10 mm. The frequency difference of two waves is about 1/2000 of the central frequency, so that the electromagnetic field patterns at both frequencies are nearly identical. The spatial structure of the wave fields can be obtained by measuring the spatial pattern of ponderomotive potential of beat waves. Figure 6 shows the time traces of the HIBP potential signal, its frequency spectrum, the line averaged electron density and central electron temperature. The deuterium target plasma is a lower single null divertor configuration with I_P=130 kA, B_T=1.15 T, $\bar{n}_e=1\times10^{19}$ m^{-3}, and a coupled fast wave power of ~ 200 kW. The fast waves are applied at t=0.635 s and the electron density increases to 1.5×10^{19} m^{-3}. The electrons are heated from 0.75 keV to 1.4 keV with 320 kW of ECH (r_{res}=0.32a) after t=0.75 s. The potential fluctuations inside plasma at the beat wave frequency (90 kHz) were clearly observed during FW pulses (Fig. 6(b)). Figure 7 shows the potential profiles of the beat wave obtained by sweeping the injected beam poloidally. The closed circle show the potential around t=0.7 s (T_e=0.75 keV) and the open circles show around t=0.8 s (T_e=1.4 keV). The measured beat wave potential does not strongly vary in this region and clearly decreases with increasing electron temperature. A comparison of these results with calculations using the full wave code TASK/WM [9] is in progress.

3.3 Pre-ionization assisted by the wave fields

Plasma production by the wave fields excited by the combline antenna was tested. Deuterium plasmas were produced reliably over a wide range of toroidal magnetic field of 0.5~2.2 T (Fig 8). The RF power required for plasma production decreases with increasing toroidal magnetic field and gas pressure (P_G). Minimum RF power is 15 kW at B_T=2.2 T and P_G=26 mPa. Figure 9 shows the time traces of V_L, I_P, central chord-integrated electron density n_eL and RF power in an RF assisted start-up experiment. RF power was applied to the antenna at t=0.15 s with B_T=1.3 T. Most of the RF power went through the

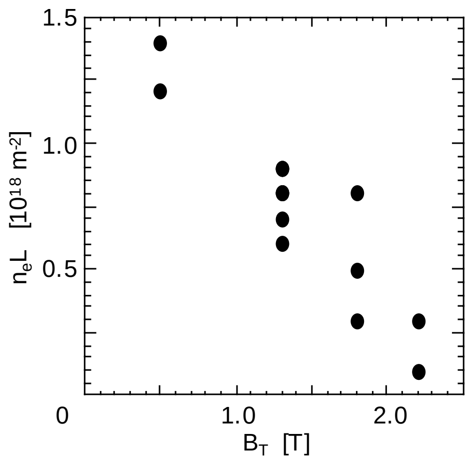

Fig. 8 Line-integrated electron density of RF plasma versus B_T: P_{RF}=85~130 kW, P_G=8~50 mPa.

antenna and absorbed by the dummy load until t=0.18 s. After a plasma is produced by the wave fields, the RF power could couple to the plasma and the unradiated power P_{out} suddenly dropped. The plasma current and the electron density increased after the loop voltage applied at t=0.2 s. Although the antenna loading was changing vigorously in this start-up phase, the wave power was injected stably into both vacuum and the start-up plasma. Even though this discharge was not optimized for low voltage start-up, the peak loop voltage decreased from 22 V without RF assist to 14 V with RF.

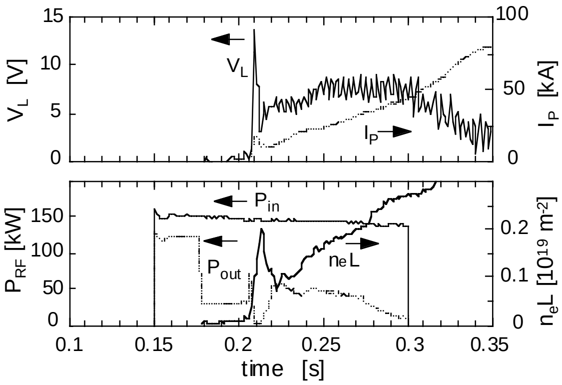

Fig.9 Time evolution of V_L, I_P, central chord-integrated electron density n_eL and RF power for the start-up assist experiment. P_{in} is the net input power to the combline and P_{out} is the power not coupled to the plasma.

4. Conclusion

A traveling wave antenna designed for fast wave current drive have been demonstrated in the JFT-2M tokamak showing good plasma coupling, power handling and excellent impedance matching capability. High energy electrons of at least 10 keV were produced in the plasma core by the highly directional fast wave. Suppression of the density increase during RF injection is needed to clarify the current drive. The combline antenna can be operated in two frequency mode and nonlinearly excite beat waves. The ponderomotive potential of the beat wave was measured directly by HIBP. The measured potential profiles of the beat wave will be compared with theoretical prediction using the full wave theory. Plasma production was demonstrated using the wave fields excited by the combline antenna over a wide range of toroidal magnetic fields (B_T=0.5~2.2 T).

Acknowledgements

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