Observation of Parametric Decay Instability on TST-2 Lower Hybrid Wave Driven Plasma*)

Yongtae KO, Yuichi TAKASE, Akira EJIRI, Naoto TSUJII, Osamu WATANABE, Hibiki YAMAZAKI, Charles P. MOELLER[1], Yasuo YOSHIMURA[2], Kotaro IWASAKI, Yuki AOI, Kyohei MATSUZAKI, James H.P. RICE, Yi PENG and Yuki OSAWA

The University of Tokyo, Kashiwa 277-8561, Japan
[1] *General Atomics, San Diego, CA 92186, USA*
[2] *National Institute for Fusion Science, Toki, 509-5292, Japan*

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Parametric decay instabilities (PDIs) in lower hybrid (LH) frequency range were observed in TST-2 in a various parameter range. LH wave measurement has been performed using four RF magnetic probes. We have been studied experiments aiming at efficient non-inductive current drive with the outboard and the top antennas installed on the outboard side and the top side of the vacuum vessel, respectively. Since PDIs are believed to deteriorate the current drive efficiency, we investigated conditions to avoid them. Operations with various combination of antennas (outboard, top), toroidal magnetic field strength and direction (CW, CCW B_T), working gas (hydrogen, deuterium) and density (normal, high) were investigated. In the outboard launch case, PDI sideband frequency δf associated with ion cyclotron quasi-modes was observed with large degree in any B_T strength in both hydrogen and deuterium plasma. On the other hand, no clear such sideband δf peak was observed only in deuterium plasma with the top launch case. Among various scenarios, the top launch with CW and CCW toroidal field in deuterium plasma seems to be desirable in terms of avoiding PDIs.

Keywords: spherical tokamak, lower hybrid wave, magnetic probe, parametric decay instability

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1. Introduction

Non-inductive current drive plays crucial role not only in center solenoid free spherical tokamak but also in future tokamak reactors. Lower hybrid current drive (LHCD) is one of the efficient current drive methods. In the TST-2 spherical tokamak, two capacitively-coupled combline antennas satisfying high directionality and low reflectivity were developed to excite LH wave. One is installed on the outboard side and the other is on the top side of the vacuum vessel [1]. The previous experiments revealed that the LHCD efficiency depends on the launching mode, especially more higher plasma current was achieved using the top launch antenna than the outboard launch antenna [2]. In the outboard launch case, we should notice that no difference in ray trajectory is expected both CW and CCW B_T, so we do not show the direction in the outboard launch case. The top (CW and CCW) launch is performed after a short pulse ($\sim$ 10 ms) power injection by the outboard antenna, in which initial small plasma current is generated. This makes smooth top launch operation.

In order to measure RF magnetic component of LHW which propagates in the SOL region, four RF magnetic probes were installed at various location in TST-2. In the previous research, we reported different characteristics of wave polarization and propagation using the probes and it was found that fast wave component was predominant in inboard region during the outboard, the top (CW) and the top (CCW) launch cases [3].

PDI is the one of issues which suppress pump wave power and degrade LHCD efficiency. PDIs such as ion cyclotron quasi-mode (ICQM) and ion sound quasi-mode were observed in other tokamak devices and there is a report that PDI prevent LHCD efficiency [4]. However there is no report about the dependence on different launching modes with RF magnetic probes locating various position.

In this work, we investigate how launching modes and other parameter condition affect the excitation of PDIs. Instead of observing ion cyclotron frequency induced by PDI directly, the measurements are performed by observing ion cyclotron harmonic sideband frequency δf peak associated with ICQMs because RF magnetic probes have poor sensitivity in the low frequency range. Using RF magnetic probes, toroidal magnetic field ($|B_T|$) scan, density scan were conducted in hydrogen and deuterium plasma. During these series of experiments, we investigated the excitation of sideband peak associated with ICQM and revealed preferable launching modes and plasma parameters for LH operation.

author's e-mail: ko@fusion.k.u-tokyo.ac.jp

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2. LH Wave Measurements

In TST-2, LH waves are launched by the outboard and the top antennas with the same frequency of 200.1 MHz, and the maximum launched power is up to $P_{\text{outboard}} \sim$ 60 kW and $P_{\text{top}} \sim$ 100 kW, respectively. In addition to the outboard and the top (CW) launches, the top (CCW) launch is performed by reversing $|B_{\text{T}}|$ direction to counter clock wise. The major radius is R = 380 mm and the outboard limiter is R = 585 mm. Figure 1 (a) shows typical time evolution of non-inductive current ramp-up discharges with three different launching modes, where plasma current is sustained either by the outboard or the top antennas. In these series of experiments, four representative RF magnetic probes, of which (R [mm], z [mm]) coordinates are MP_{inU}: (+113, +327) and MP_{inL}: (+113, −177) on the upper and lower inboard sides, respectively, MP_{bott}: (+329, −450) on the bottom limiter and MP_{out}: (+585, 0) on outboard limiter, were chosen to measure PDI spectrums. All RF magnetic probes are located in one poloidal plane at a toroidal angle $\phi = -90°$ measured from the center of the outboard antenna, that is $\phi = -30°$ measured from the center of the top antenna (Fig. 2 in [3]). LH waves are measured by two oscilloscopes with bandwidth 500 MHz and 1 GHz. Measured spectra is normalized by LH injection power. Figure 1 (b) shows the typical LH wave spectra observed with MP_{inU} and MP_{inL} probes at 50 ms of the outboard launch operation shown in Fig. 1 (a). Spectral peaks thought to be ion cyclotron harmonic side-

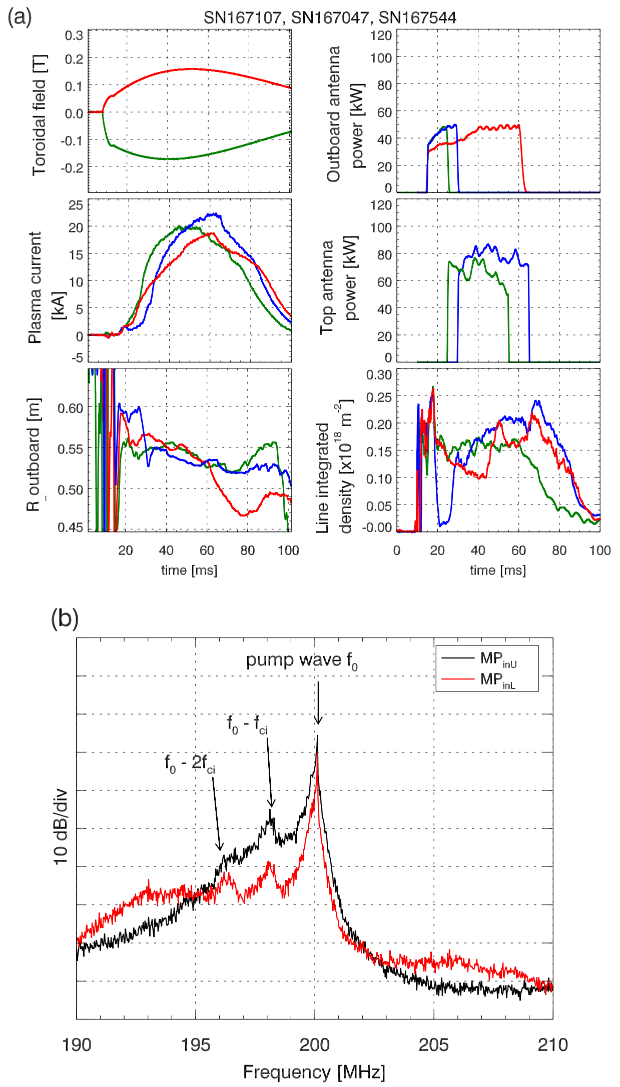

Fig. 1 (a): The typical time evolutions of non-inductive ramp-up discharges. Red, blue, green curve represents the outboard-, the top (CW)-, the top (CCW)- launch cases, respectively. (b): The typical LH wave spectrum measured by MP_{inU} and MP_{inL} probes during the outboard launch case shown in (a).

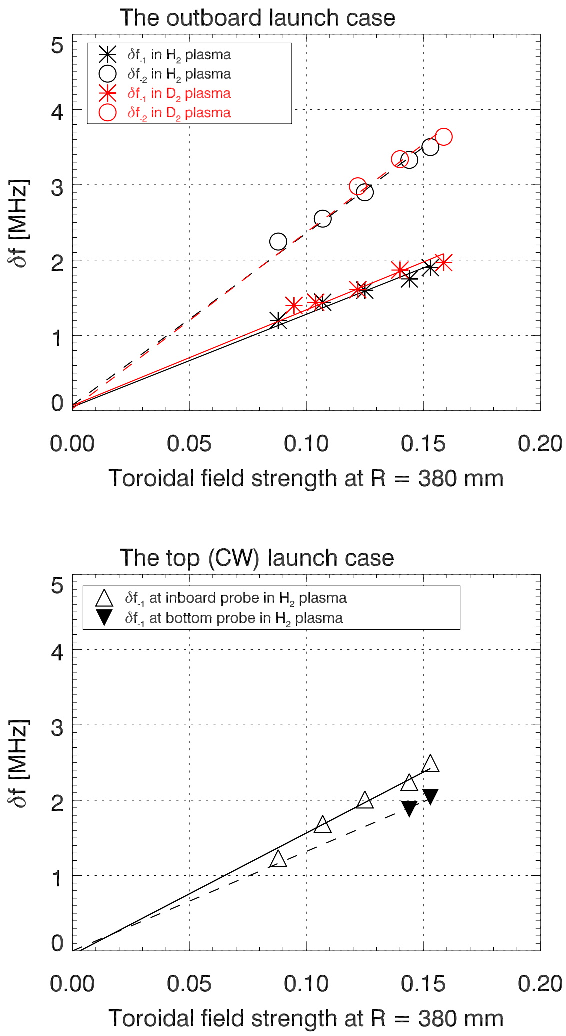

Fig. 2 TF dependence of $\delta f_{\pm n} = \pm n f_{ci}$. The upper figure shows the outboard launch case in hydrogen and deuterium plasma. Asterisk and circle symbols indicate the difference between pump wave frequency and fundamental and second harmonic sideband peak frequency δf_{-1} and δf_{-2}, respectively. The bottom figure shows the top (CW) launch only in hydrogen plasma. In this figure, the up-pointing triangle and the bottom-pointing triangle symbols indicate the data observed by inboard side probes and outboard side probes, respectively.

bands at frequencies $f_0 \pm nf_{ci}$ are denoted as $\delta f_{\pm n}$. In the next section, we surveyed various conditions which parameter affects the excitation of sideband frequency δf associated with ICQMs.

3. PDI Measurements

3.1 Toroidal field dependence in hydrogen and deuterium plasma

In order to identify and classify ICQMs, toroidal field (B_T) scan was performed for hydrogen plasma. The other parameters are as follows: I_p = 10 - 15 kA, line integrated density n_e = 0.8 - 1.5 × 10^{17} m^{-2}, $P_{outboard}$ ~ 60 kW, P_{top} ~ 80 kW. In these experiments, sideband peaks δf_{-1} and δf_{-2} associated with ICQMs move to the lower frequency region with the increases in B_T (Fig. 2).

In the outboard launch case in hydrogen plasma (Fig. 2 upper figure), δf_{-1}, δf_{-2} are dominant in the lower sideband of pump wave and also observed linear dependency with TF among in inboard side, bottom side and outboard side probes. From observed δf_n peak, magnetic field and radial location where PDI occurred were estimated. The calculation shows that δf_{-1} dominantly caused in R = 425 - 477 mm, δf_{-2} caused in R = 454 - 507 mm. Taking into account that magnetic axis of the plasma is locate around R = 350 mm, all the observed PDIs were invoked in the outer region, and some of them could reach the inboard side. In these experiments, parameters such as plasma size (last closed flux surface) and line integrated density were not identical. This might affect differences in radial position among same δf, but the reason why the positions of fundamental and second harmonic of δf were separated by about 30 mm is not understood well.

On the other hand, in the top (CW) launch case in hydrogen plasma (Fig. 2 bottom figure), sideband peak in both lower sideband δf_{-1} was observed. $|B_T|$ dependence agrees with the dependence in the outboard launch case, but there are differences on $\delta f_{\pm n}$ between inboard side probe and outboard side probe. Radial position where PDIs were excited was calculated as well. With inboard probes, the frequency δf_{-1} occurred at R = 355 - 373 mm, but R = 435 - 444 mm with outboard probes cases. This result indicates that there are two radial locations where PDI were excited and wave propagation path branches two ways so that waves launched by top antenna pass through inboard region and reached probes after waves branch at somewhere inboard region.

In addition to hydrogen plasma, $|B_T|$ scan was conducted in deuterium plasma (red asterisk and circle symbols in upper figure Fig. 2). However, in the outboard launch case, the mode frequencies are the same in both hydrogen and deuterium plasma, while we expected that

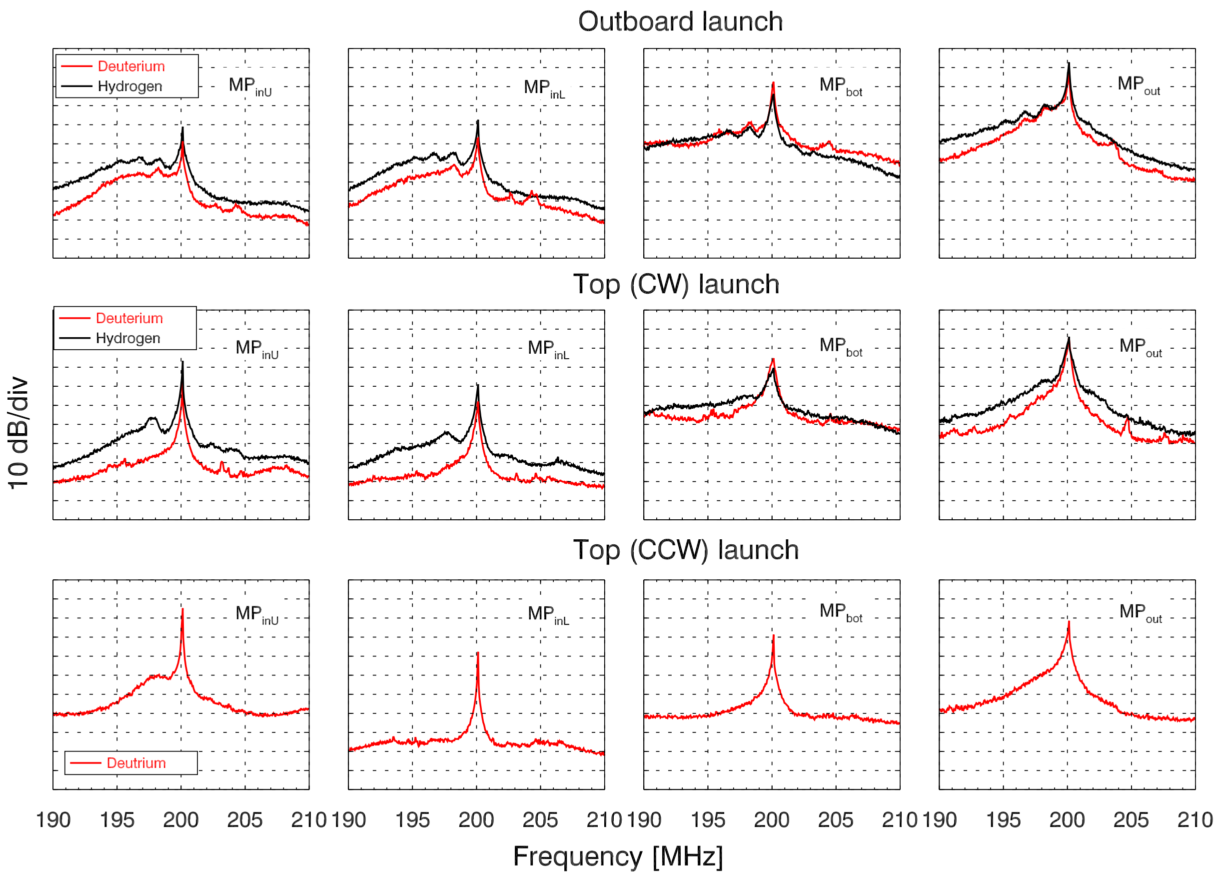

Fig. 3 Power in hydrogen (black) and deuterium (red) plasma in the outboard and the top (CW and CCW) launch cases.

sideband frequency $\delta f_{\pm n}$ would be half of those in the hydrogen plasma. One possibility of this reason is that the effect of hydrogen gas recycling from vessel wall could not be negligible in this deuterium plasma experiment which was conducted just after hydrogen experiment. In the top (CW) and the top (CCW) cases, no clear sideband frequencies were observed at any $|B_T|$ in deuterium plasma. the top (CW) case is described in the next subsection and gas species dependence with the top (CCW) case should be investigate in the future. So the figure of $|B_T|$ dependence with the top (CW and CCW) cases in deuterium plasma are not posted on this paper.

3.2 Comparison between hydrogen and deuterium plasma

LH wave spectra observed in the outboard and the top (CW) launch cases in hydrogen and deuterium plasma are shown in Fig. 3. Experiments were performed with the following parameters: I_p = 10 - 14 kA, line integrated density n_e = 0.9 - 1.2 × 10^{17} m^{-2}, $|B_T|$ = 0.14 T, $P_{outboard}$ ~ 60 kW, P_{top} ~ 80 kW. In hydrogen plasma experiments with the outboard launch, lower side component of the pump wave became broader than those in deuterium plasma, especially for the spectrum obtained by the near outboard antenna probe MP_{out} and far antenna probes MP_{inU} and MP_{inL}. Besides, small amplitude of peaks appeared in the upper side of the pump wave frequency for all probes in deuterium plasma. Additionally, it is interesting that the same sideband frequency δf was shown in spite of different gas species. In the top (CW) launch case, clear deferences between hydrogen and deuterium plasma were observed. Sideband frequency δf was not clearly observed in deuterium plasma and large spectral broadening of the pump wave were suppressed, especially in inboard probe spectra. From these results, wave propagation loss due to PDIs or scattering effect is smaller in deuterium plasma. The same tendency was observed in the top (CCW) case as well.

3.3 Density dependence in deuterium plasma

Density scan was performed by puffing additional gas during discharges. In this experiment, line integrated density was not identical among launching modes, but it gives qualitative understanding. The experimental result is shown in Fig. 4. Typical experimental parameters are as follows, I_p = 18 kA, $|B_T|$ = 0.18 T, $P_{outboard}$ ~ 50 kW for the outboard launch, I_p = 12 kA, $|B_T|$ = 0.18 T, P_{top} ~ 70 kW for the top (CW) launch and I_p = 17 kA, $|B_T|$ = 0.18 T, P_{top} ~ 70 kW for the top (CCW) launch. In the outboard launch case, the pump wave frequency width near the antenna increased with the density increase. In contrast, lower sideband component decreases by about 10 dB

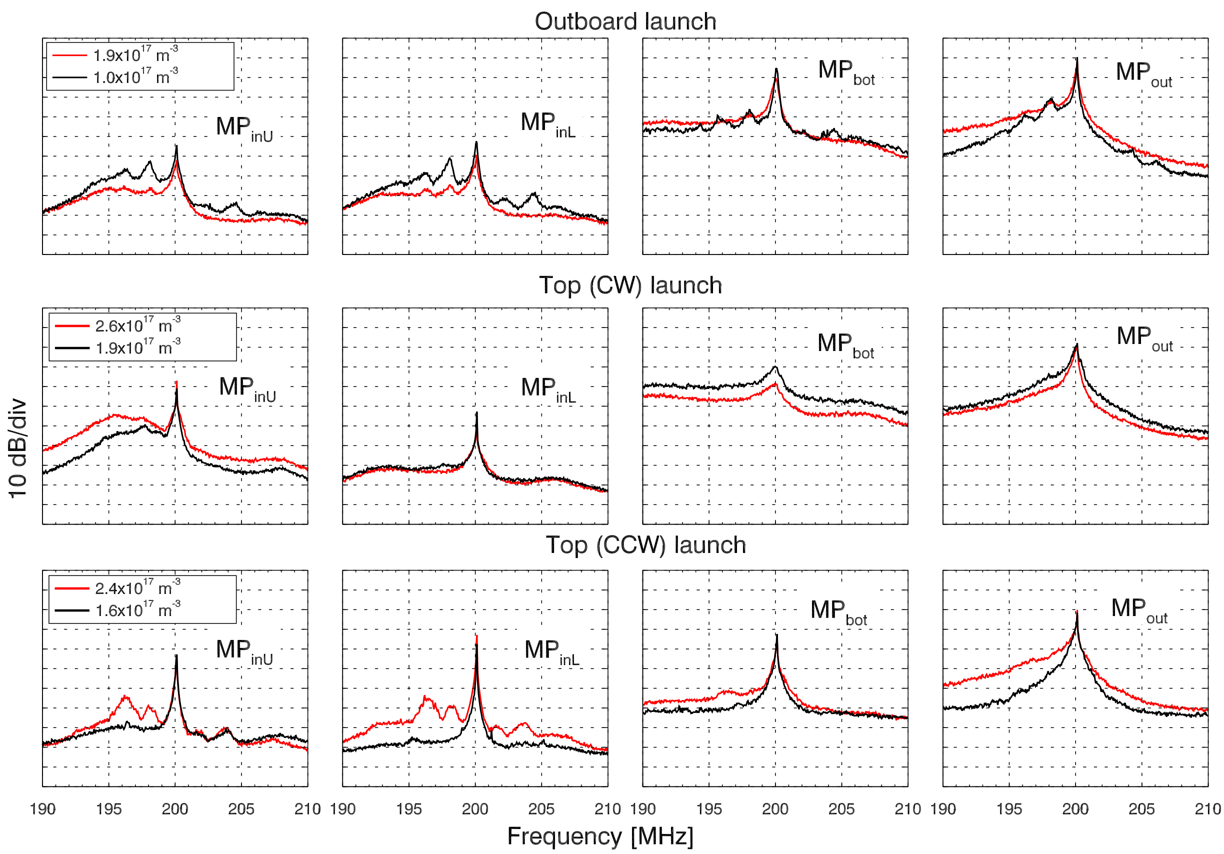

Fig. 4 Density dependence of LH wave in deuterium plasma in the outboard and the top (CW), the top (CCW) cases. Normal operation (black) and additional gas puff (red).

in the inboard probe spectra (i.e., far from antenna). Possible reasons for these phenomena is scattering losses due to enhanced density fluctuations in SOL region [5, 6] or ion sound quasi-mode [7, 8]. To clarify the above explanation more systematically, experiments including density measurement by electrostatic probes nearby RF magnetic probe is needed. A similar pump wave frequency broadening was observed in the top (CW) launch case. In the top (CCW) case, the inboard probe shows that sideband peak appeared at the lower side in high density case, whereas almost flat sideband spectrum is observed in normal density case. In contrast to the top (CW) launch case, pump wave broadening was prominent at outboard probe in high density case in contrast to the top (CW) launch.

4. Summary

In this study, the measurement of waves during LH injection using RF magnetic probes were performed. We investigated ion cyclotron harmonic sideband frequency associated with ICQMs in various plasma conditions by comparing mainly the outboard launch and the top (CW) launch. In TF scan experiments, radial position where PDI occurred was estimated by following ion cyclotron harmonics δf_n. LH waves launched by the outboard antenna decayed to ICQMs at $R \sim 425$ - 477 mm and $R \sim 454$ - 507 mm. In the top (CW) launch case, PDIs invoked at different two radial positions $R \sim 355$ - 373, 435 - 444 mm. Obvious differences among launching modes were observed between in hydrogen and deuterium plasma. Besides the suppression of LH spectrum broadening in deuterium plasma with both the outboard and the top (CW) cases, sideband frequencies were not observed with the top (CW and CCW) case. Scattering loss of LH waves were also observed in density scan experiment. This scattering loss is though to cause LH spectral broadening near launching antenna. These results indicate that the top (CW and CCW) launch in deuterium plasma operation seems to be more desirable in terms of mitigation of PDI. However, the influence of PDI on the current drive efficiency seems to be limited, because there is no evidence that current drive efficiency becomes high without PDI. As a future plan, following investigation is needed. Numerical analysis such as ray-trace or full wave calculation including PDI dispersion might give more quantitative understanding of the experimental results. Clarification of the relationship between PDI and density fluctuation measured by electrostatic probes is necessary for understanding of PDI research.

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