Frequency Dependence of Fast Magnetic Fluctuations in TPE-RX Reversed-Field Pinch Plasma

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We have measured fast magnetic fluctuations (> 10 kHz) using a complex edge probe in the edge region of TPE-RX reversed-field pinch plasma. We observed that the frequency of magnetic fluctuation at the peak power in the frequency spectrum varies with time, and this frequency variation is determined by the values of pinch and reversed parameters, although the amplitude of the fast magnetic fluctuations are almost independent of those parameter values.

Keywords: reversed-field pinch (RFP), pinch parameter, magnetic fluctuation

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The reversed-field pinch (RFP) is a magnetic confinement system used for nuclear fusion research [1]. The RFP configuration is obtained due to magneto-hydrodynamic (MHD) relaxation, and sustained by the RFP dynamo, where the nonlinear interactions of core resonant tearing modes play a major role. Thus, the core confinement of standard RFP is dominated by magnetic fluctuations due to tearing modes [2]. The characteristics of the RFP plasma are indicated by the pinch parameter $\Theta = B_p(a)/\langle B_t \rangle$ and reversed parameter $F = B_t(a)/\langle B_t \rangle$. Here, $B_p(a)$ and $B_t(a)$ are the poloidal and toroidal magnetic fields at the plasma surface, respectively, and $\langle B_t \rangle$ is the volume-averaged toroidal magnetic field. The values of Θ and F are important for the confinement properties of RFP plasmas and can be varied by the selection of operating parameters. For example, the improved high theta mode (IHTM) on the TPE-1RM20 device (obtained with the high Θ value) demonstrates high beta and improved energy confinement [3]. The quasi-single helicity (QSH) state has improved particle confinement [4] and the pulsed poloidal current drive (PPCD) operation has demonstrated high beta, improved particle and energy confinements [5], and magnetic fluctuation reduction [6] on the TPE-RX device. Since the RFP transport is strongly related to the magnetic fluctuations, a more comprehensive understanding of RFP confinement is required by studying the characteristics of the magnetic fluctuations in the discharges with different Θ and F values. In this study, we describe the dependence of the frequency characteristics of fast magnetic fluctuations, at frequencies higher than 10 kHz, in some detail.

Experiments have been performed in the TPE-RX device [7]. TPE-RX is one of the three largest RFP machines in the world, whose major/minor radii are $R/a = 1.72\,\mathrm{m}/0.45\,\mathrm{m}$. TPE-RX has a multilayered shell system that provides MHD mode stabilization and equilibrium control. The shell proximity is $b/a = 1.08$ (b is the minor radius of the innermost shell). The operating conditions used in this study were the plasma current, $I_p \sim 200\,\mathrm{kA}$, $\Theta = 1.5\text{-}1.8$, $F = -0.1$ to -0.3 and a pre-fuelled deuterium gas.

The TPE-RX has an extensive magnetic measurement system (MMS) situated outside a stainless steel vacuum vessel [8]. Many plasma parameters are measured by the MMS. To date, however, a detailed study of the high-frequency magnetic fluctuations has not been possible, because the shielding effect of the vacuum vessel has restricted measurements of the high-frequency portion of the magnetic fluctuations to less than 10 kHz. To solve this problem, a complex edge probe (CEP) has been installed inside the vacuum vessel [6,9]. The high-frequency portion of the magnetic fluctuations can be measured by the CEP, which is set at $r/a = 1.00$. The CEP has three magnetic pickup coils of toroidal, poloidal, and radial directions. The pickup coils are connected to the differential amplifier through a low-frequency pass filter with a cut-off frequency of 1.5 MHz. The signals are digitized with 12-bit digitizers at a 250 ns sampling interval with the WE7116 ADC system (Yokogawa Electric). The output voltage signal from the CEP becomes very small for slow fluctuations with a frequency less than 7 kHz, and cannot be measured with the dynamic range of the ADC system. The lower limit of the frequency region of the CEP is 7 kHz for the fluctuation level under the present operating conditions [9].

Figure 1 shows the time evolutions of I_p, Θ, F, the

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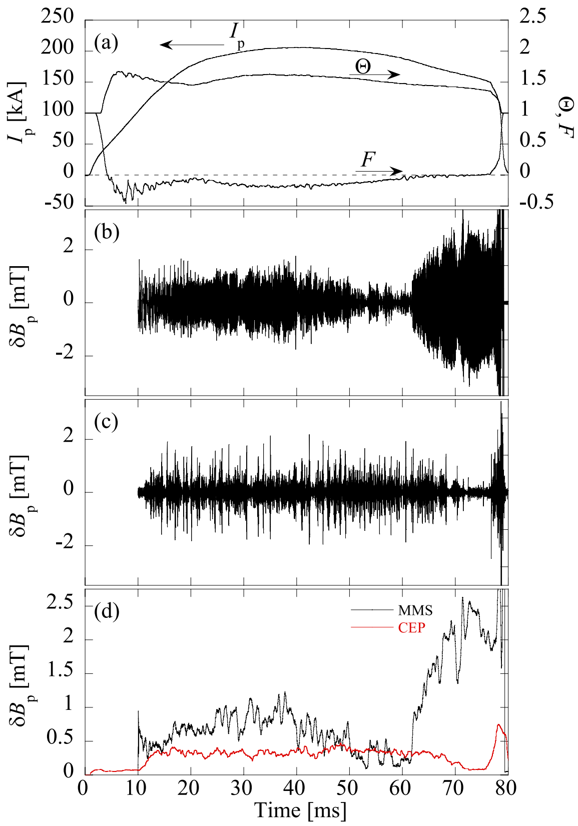

Fig. 1 Time evolutions of (a) plasma current I_p, pinch parameter Θ, reversed parameter F; (b) poloidal magnetic field amplitude δB_p measured by MMS; (c) δB_p measured by CEP in ordinary discharge; and (d) moving average of δB_p obtained from the root mean square of the MMS and CEP.

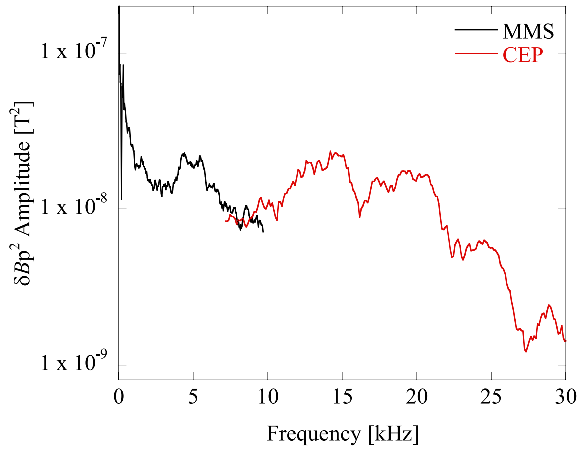

Fig. 2 Smoothed power spectra of δB_p from MMS and CEP.

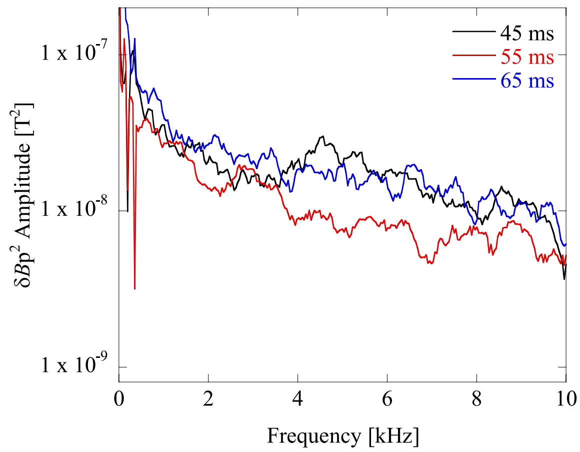

Fig. 3 Smoothed power spectra of δB_p from MMS at three different time windows.

fluctuation amplitude of the poloidal magnetic field amplitude δB_p measured by the MMS, and δB_p measured by the CEP in ordinary discharge. The maximum values of Θ and F were about 1.6 and −0.18, respectively. The δB_p measured by the MMS varies with time, decreasing once between 50 and 62 ms with a decaying Θ value, and increasing after 62 ms when the plasma rotation is slowing down and finally, the magnetic fluctuation is locked to the vacuum vessel wall. The locked mode takes place at 68 ms and lasts until 80 ms. The low-frequency portion of the fluctuation increases because of the appearance of the locked mode [9]. The δB_p measured by the CEP, does not change roughly from 14 to 68 ms, and decreases after 68 ms because the high-frequency portion of the fluctuation decreases with the appearance of the locked mode. The amplitude power spectra of δB_p measured by the MMS and CEP are shown in Fig. 2. The distance between the MMS and CEP is 40 mm. In the present analysis, only the global mode of the MHD fluctuations are considered, with frequencies less than 50 kHz and wavelengths longer than 1 m. Therefore, the small distance between the MMS and CEP is not important for comparing the signals. They are estimated between 30 and 50 ms. The MMS has sensitivity to frequencies less than 10 kHz. To investigate the change of δB_p level measured by the MMS, the averaged amplitude power spectra of δB_p for three different time windows are shown in Fig. 3. Each amplitude power spectrum is estimated for the 10 ms time durations (e.g., 45 ms indicates between the 40 and 50 ms interval). Comparing the 55 ms spectrum with those of 45 and 65 ms, it is shown that the decrease of δB_p in the initial phase is caused by a decrease in the frequency region, between 4 and 10 kHz, and the increase of δB_p in the later phase is caused by an increase in the region below 4 kHz. The slow fluctuation amplitudes at frequencies less than 10 kHz depend on the Θ value, because the value changes during each period as shown in Fig. 1 (a). The slow fluctuation is provided by the rotation of the magnetic fluctuation due to the tearing mode [9].

We can examine a frequency region above 5 kHz using the CEP; strong power is observed between 10 and 25 kHz. The time evolutions of the high-frequency portions of the amplitude power spectrum of δB_p, measured by the CEP, and the frequency f_{PB} at which the δB_p power reaches max-

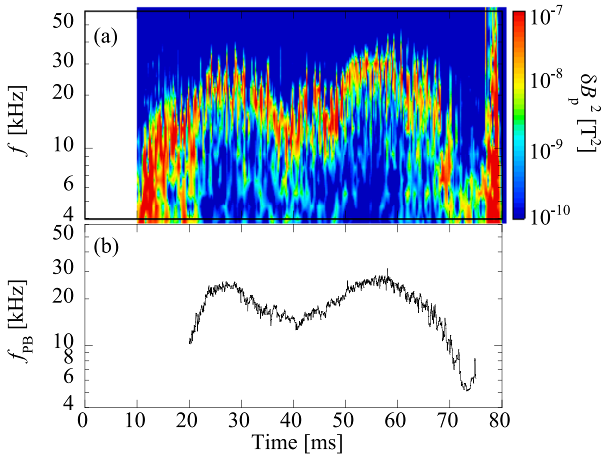

Fig. 4 Time evolutions of (a) the power spectra of δB_p and (b) the peak frequency of poloidal magnetic field amplitude power f_{PB} measured by CEP in ordinary discharge.

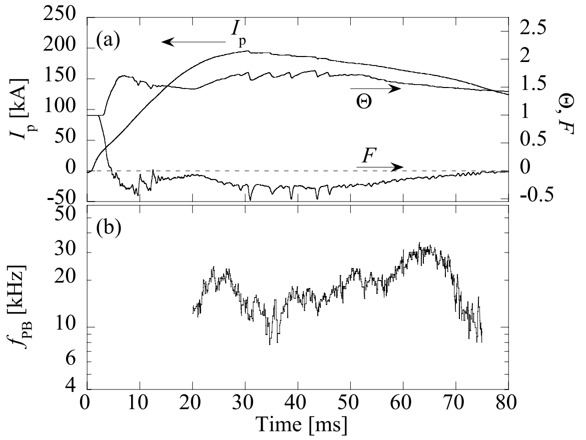

Fig. 5 Time evolutions of (a) I_p, Θ, F, and (b) f_{PB} in high Θ discharge.

imum are shown in Fig. 4. Here the f_{PB} is determined from the δB_p power frequency spectrum above 5 kHz. The f_{PB} increases to about 25 kHz before 28 ms and decreases to about 15 kHz between 30 and 40 ms. The maximum f_{PB} of about 27 kHz occurs at 57 ms in the later part of discharge. The δB_p level decreased with f_{PB} less than 10 kHz after 68 ms. It is shown that the frequency characteristics and power spectra of δB_p change with time.

To investigate the dependence of the pinch parameter, the time evolutions of I_p, Θ, F, and f_{PB} in high Θ discharge are shown in Fig. 5. It is shown that the saw-toothed crash events took place for $F \sim -0.4$, but the plasma rotation continued just after the saw-toothed crash. The average values of Θ and F were about 1.8 and -0.25, respectively, before 60 ms. We observed that the total amplitude of δB_p measured by the CEP did not change, being roughly the same as that for an ordinary discharge. The f_{PB} increased step-by-step, with the saw-toothed crash after 30 ms, and a

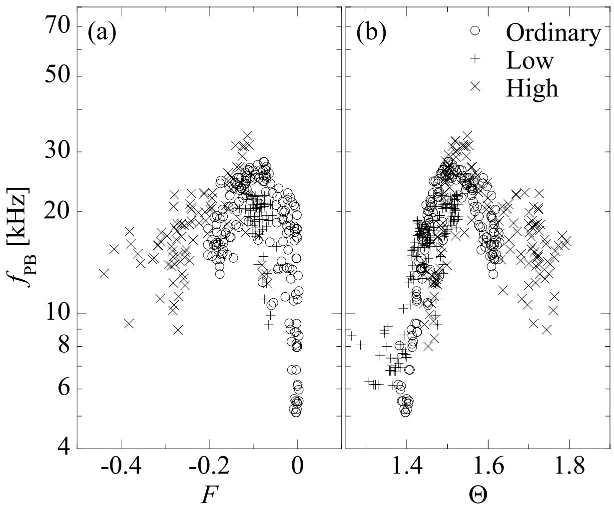

Fig. 6 Dependences of f_{PB} on (a) F and (b) Θ at about the same time interval of 20 - 75 ms, for ordinary, low Θ, and high Θ discharges.

maximum f_{PB} of about 35 kHz at 65 ms was obtained.

The dependence of f_{PB} on Θ and F at about the same time (between 20 and 75 ms for ordinary, low Θ, and high Θ discharges) is shown in Fig. 6. The low Θ discharge is $\Theta < 1.5$ and $F > -0.1$. The f_{PB} became maximum at $F \sim -0.1$ and decreased in deeper F. The f_{PB} became maximum at $\Theta \sim 1.55$ and decreased for higher Θ. The f_{PB} also decreased for lower Θ. It is found that the frequency at the maximum power depends only on the Θ and F values and does not depend on individual operating conditions. Interestingly, on the other hand, the total amplitude of the fast fluctuation of δB_p measured by the CEP and MMS is almost independent of the Θ and F values. The main frequency band of fast magnetic fluctuations move to a lower band with a higher Θ value.

In summary, we measured fast poloidal magnetic fluctuations using the CEP in the edge region of TPE-RX RFP plasma. We have shown that the frequency at the maximum value in the frequency power spectrum has a clear dependence on the Θ and F values, i.e., it is mainly determined by the Θ and F values only. The amplitude of fast magnetic fluctuation, however, is almost independent of the Θ and F values.

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