Dependence of MHD Burst Events and Velocity Distribution Deformation on Magnetic Field Direction in LHD Plasma

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We conducted energetic particle-induced MHD burst excitation experiments on the Large Helical Device (LHD) to investigate how these events—and the associated deformations of the ion velocity distribution—depend on the direction of the magnetic field. Wavelet cross-power spectrum analysis revealed that the toroidal propagation direction of the MHD bursts reverses with the magnetic field. Fast charge exchange recombination spectroscopy (fast-CXRS) was used to measure the temporal evolution of the carbon ion velocity distribution function. A bipolar signature in velocity space, as well as the resonant velocity, varied with the magnetic field direction. A strong correlation was observed between the chirping frequency and the corresponding resonant velocity, and the phase velocity was found to closely match the resonant velocity, including the sign of the propagation direction.

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In thermonuclear fusion plasmas, the ion thermal velocity is typically high enough for the plasma to be considered effectively ion-ion collisionless on the time scale of MHD. Under such conditions, it is crucial to elucidate the mechanisms by which bulk ions gain energy from energetic particles via collisionless interactions. This is particularly important in the context of alpha channeling [1], where energy is transferred from fusion-born alpha particles to bulk ions through wave-particle interactions.

A similar process has recently been investigated in experiments on the Large Helical Device (LHD) [2–4]. In these experiments, fast charge exchange recombination spectroscopy (fast-CXRS) [5, 6] was used to observe a bipolar signature in the velocity distribution function (VDF) of carbon and bulk ions during energetic particle-induced magnetohydrodynamic (MHD) burst events. The bipolar signature refers to a characteristic perturbation pattern in the VDF— negative at lower velocities, crossing zero, and becoming positive at higher velocities—indicating a modification of ion velocities due to wave-particle interactions. These signatures were identified through agreement between the phase velocity of the MHD bursts and the resonant velocity of the ions [2].

Based on these findings, it is expected that if the propagation direction of the MHD bursts changes, the polarity of the bipolar signature in the VDF should also reverse. However, these expectations have not yet been fully verified, which is benefitial to verify this expectation to enhance understanding the physics and the diagnostic reliability of fast-CXRS. To investigate this, we conducted experiments on LHD under different magnetic field directions—clockwise (CW) and counterclockwise (CCW)—as previous studies suggest that the propagation direction of MHD bursts is governed by the magnetic field direction and tends to be opposite to it [7]. The central ion temperature, electron temperature, and electron density were approximately 6 and, 3 keV, and $< 1.0 \times 10^{19}$ m^{-3}, respectively, and the magnetic field strength was set to 2.75 T, consistent with previous studies [2].

We employed perpendicular neutral beam injection (NBI) both as a source of energetic particles and as the diagnostic beam for fast-CXRS. The fast-CXRS system was used to measure the carbon ion VDF with sufficient time resolution to capture its temporal evolution during MHD burst events. Assuming that the resonant condition is satisfied only for the toroidal components, as shown in previous studies [2, 3], the measurement was utilized the toroidal line of sight, where contributions from non-toroidal velocity components are negligible under the present experimental condition [8]. The propagation direction of the MHD bursts was determined using a toroidal magnetic probe array. To take advantage of the quasi-periodic nature of the bursts, a conditional sampling technique was employed [2–4], with reproducible data from 10 CW and 16 CCW shots obtained during the 2022 experimental campaign. Wavelet spectrum analysis was applied to capture frequency chirping. The Morlet wavelet was employed as the

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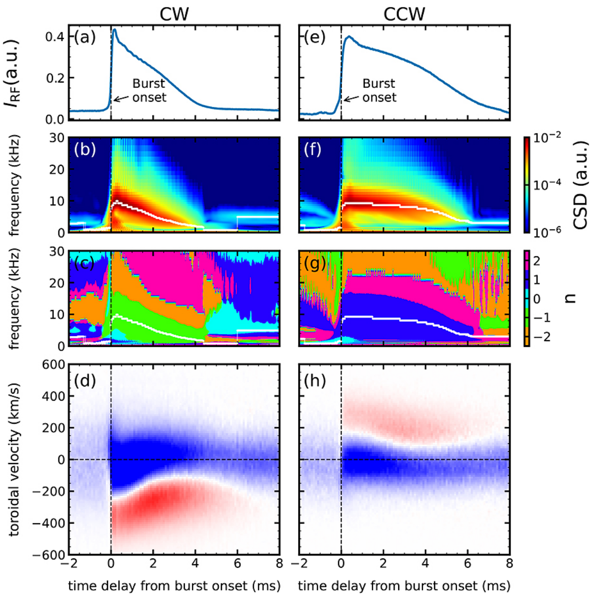

Fig. 1. Conditionally averaged time evolution of radio frequency fluctuation intensity I_{RF}, wavelet cross-power spectrum density (CSD), instantaneous toroidal mode number (n) spectrum, and the deviation of the carbon ion VDF from a Maxwellian for the CW (a–d) and CCW (e–h) cases. The green and blue colors in (c) and (g) indicate the toroidal mode number $n = +1$ and -1, respectively. White lines in (b), (c), (f), and (g) indicate the frequency at which the wavelet cross-power spectrum reaches its maximum at each time.

mother function for the wavelet analysis, and the corresponding Fourier frequency can be obtained from the wavelet scale. The toroidal mode number was determined using wavelet cross-power spectrum analysis between magnetic probe signals at toroidal angles of $\phi = 18°$ and 90°.

A typical conditionally averaged time evolution of the MHD burst events is shown in Fig. 1. In both CW and CCW cases, downward frequency chirping was observed around 10 kHz. As shown in Figs. 1(c) and (g), analysis of the wavelet cross-power spectrum revealed a toroidal mode number of $n = +1$ for CW and $n = -1$ for CCW, respectively. Here, the sign convention is such that $n > 0$ corresponds to CW propagation and $n < 0$ to CCW. These results are consistent with previous observations. In both cases, deformation of the VDF from a Maxwellian shape was observed. A clear bipolar signature was also evident, with its polarity reversed between the CW and CCW cases, as shown in Figs. 1(d) and (h).

Next, we compared the resonant velocity evaluated from the VDF with the phase velocity of the MHD bursts. The resonant velocity was evaluated at the zero-crossing point of the bipolar signature in the VDF. Since strong coherence between ECE and magnetic probe signals, the phase velocity can be calculated from the chirping frequency and toroidal mode number as $v_{\mathrm{p}} = 2\pi f R_{\mathrm{excited}}/n$, where R_{excited} is the major radius of the MHD burst excitation region, estimated to be 4.25 m [2]. Figure 2 shows the relationship between the resonant and phase velocities for both CW and CCW cases. The phase and resonant velocities showed similar absolute

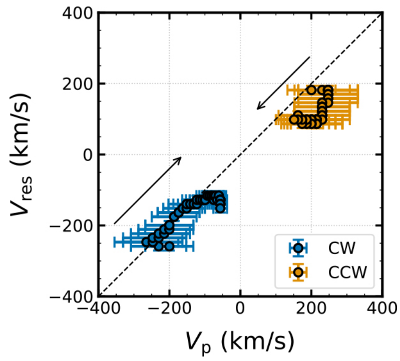

Fig. 2. Scatter plot of the resonance velocity v_{res} and the phase velocity v_{p} for CW (blue) and CCW (orange) cases. The dotted line indicates the $v_{\mathrm{res}} = v_{\mathrm{p}}$ line. Each arrow indicates direction of time evolution of the resonance velocity and phase velocity. The error bars determined by measurement resolutions.

values, and good agreement was found in both cases, including the sign of the propagation direction and the temporal behavior associated with frequency chirping. These results indicate that the bipolar signature in the VDF is indeed related to the MHD burst events and support the reliability of fast-CXRS observations.

In summary, we conducted experiments on LHD to investigate how MHD burst events and the deformation of the carbon ion VDF depend on the magnetic field direction. By analyzing the wavelet cross-power spectrum, we identified the toroidal mode number and chirping frequency, confirming that the propagation direction of the MHD bursts changes with the magnetic field direction. A reversal in the polarity of the bipolar signature in the carbon ion VDF was observed when the magnetic field direction was switched from CW to CCW. Furthermore, a strong correlation was found between the chirping frequency and the corresponding resonant velocity, with the phase velocity closely matching the resonant velocity, including its sign. These findings offer valuable insights into the mechanisms underlying burst event generation.

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[1] A.J. Fetterman and N.J. Fisch, Phys. Rev. Lett. **101**, 205003 (2008).
[2] K. Ida *et al.*, Commun. Phys. **5**, 228 (2022).
[3] T. Kobayashi *et al.*, Proc. Natl. Acad. Sci. USA **121**, e2408112121 (2024).
[4] Y. Kawachi *et al.*, Rev. Sci. Instrum. **94**, 103505 (2023).
[5] T. Kobayashi *et al.*, Rev. Sci. Instrum. **96**, 033502 (2025).
[6] M. Yoshinuma *et al.*, Plasma Fusion Res. **19**, 1402037 (2024).
[7] X.D. Du *et al.*, Phys. Rev. Lett. **114**, 155003 (2015).
[8] M. Yoshinuma *et al.*, Plasma Fusion Res. **3**, S1014 (2008).