Study on the Effect of Sidebands of KSTAR-like Traveling Wave Antenna Power Spectrum on Helicon Wave Current Drive in EXL-50U Spherical Torus Plasma

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Abstract

This paper investigates the influence of sidebands in the spectra of two KSTAR-like traveling wave antennas (TWAs) on helicon current drive (HCD) in the spherical tokamak EXL-50U. First, two sets of 476 MHz KSTAR-like TWAs are designed based on optimized parameters obtained through extensive parameter scanning; their spectra feature the same parallel refractive index N = −3.2 corresponding to the main peak but different sidebands. Then, by comparing the current driven by them with that driven by a Gaussian-like spectrum, the effects of sidebands in these two TWA spectra on HCD are discussed. The analysis reveals that under medium-density, low-magnetic-field and low-density, high-magnetic-field conditions, the sidebands have a significant impact on HCD, with a maximum absolute difference in driven current of 178 kA between the two KSTAR-like TWA spectra and the Gaussian-like spectrum at the same injection power. Higher temperature leads to an increased impact of sidebands on HCD. The sidebands not only affect the magnitude of HCD, but also cause the current peak to shift toward the plasma center or edge. Under certain conditions, narrow sidebands with parallel refractive index close to the strong Landau damping condition may be beneficial for improving the driven current magnitude and local control. This research provides guidance for the design of RF antennas and HCD experiments.

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Study on the Effect of Sidebands of KSTAR-like Traveling Wave Antenna Power Spectrum on Helicon Wave Current Drive in EXL-50U Spherical Torus Plasma

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This paper investigates the influence of sidebands in the power spectra of two KSTAR-like traveling wave antennas (TWAs) on helicon current drive (HCD) in the EXL-50U spherical tokamak. First, two sets of 476 MHz KSTAR-like TWAs are designed based on optimized parameters obtained through extensive parameter scanning. These antennas produce spectra with the same parallel refractive index $N_{\|} = -3.2$ for the main peak but different sideband characteristics. By comparing the current driven by these antennas with that driven by a Gaussian-like spectrum, we discuss the effects of the sidebands on HCD. The analysis reveals that under conditions of medium-density/low magnetic field and low-density/high magnetic field, the sidebands significantly impact HCD, with a maximum absolute difference in driven current of 178 kA between the two KSTAR-like TWA spectra and the Gaussian-like spectrum at the same injection power. Higher temperature leads to an increased impact of sidebands on HCD. The sidebands not only affect the magnitude of HCD but also cause the current peak to shift toward the plasma center or edge. Under certain conditions, narrow sidebands with parallel refractive index close to the strong Landau damping condition may be beneficial for improving the driven current magnitude and enabling local control. This research provides guidance for the design of RF antennas and HCD experiments.

Keywords: Helicon current drive, Traveling wave antenna, Sidebands, Localization of current distribution

INTRODUCTION

Non-inductive current drive in plasma represents one of the critical challenges for achieving stable operation of fusion devices based on the tokamak concept [?]. To maintain reverse shear or negative shear magnetic field configurations for high-performance steady-state operation, the current must be driven off-axis. Various methods exist for current drive utilizing auxiliary heating in tokamak plasmas, among which helicon current drive (HCD), also known as fast wave current drive in the lower hybrid range of frequencies, is regarded as a promising tool for driving off-axis currents in reactor-grade plasmas.

In high-beta plasma, due to the large harmonic number (where the angular frequency ω is approximately 30-50 times the ion cyclotron frequency ω_{ci}) [?, ?], helicon wave ion cyclotron damping can be quite weak, while electron damping can be strong. Since helicon wave damping on electrons is strong at high beta, wave power can be significantly attenuated before reaching the plasma center, enabling off-axis current drive and radial deposition control through manipulation of the launched wave spectrum [?].

Significant progress has been made in helicon wave heating and current drive. The importance of helicon waves for current drive was first recognized through ARIES reactor studies [?]. HCD experiments in the NSTX spherical tokamak demonstrated central electron temperatures of 4 keV and driven currents of approximately 100 kA [?]. Traveling wave antennas offer numerous advantages, including load resilience, narrow $N_\parallel$ spectrum, good plasma coupling, and excellent impedance matching capability [?, ?]. A 12-element combline TWA exhibited the expected characteristics and produced at least 10 keV high-energy electrons in the plasma core during JFT-2M helicon current drive experiments. Experiments with low-power (100-300 kW) combline-type TWAs and strong coupling have confirmed the feasibility of helicon current drive systems for KSTAR [?] and DIII-D [?]. Recently, a new MW-level helical TWA and a 30-module TWA for helicon wave current drive have been successfully installed in KSTAR and DIII-D, respectively [?, ?, ?].

Numerical calculations have verified the high efficiency of helicon wave heating and current drive in tokamaks using the ray-tracing code GENRAY with the Ehst-Karney formula, the Fokker-Planck code CQL3D incorporating quasilinear effects, the full-wave code AORSA, and the finite element solver COMSOL [?, ?, ?]. Using the GENRAY/CQL3D package, simulations demonstrate an optimal launched $N_\parallel$ of approximately 1.6 for the CFETR hybrid scenario, with a maximum helicon wave current drive efficiency of $2.8 \times 10^{19}\,\mathrm{A} \cdot \mathrm{W}^{-1} \cdot \mathrm{m}^{-2}$ [?]. For a DIII-D case study, analysis reveals that off-axis current drive is 2 to 4 times more efficient than off-axis neutral beam current drive under the same conditions, with helicon current drive efficiency remaining essentially constant for launched $N_\parallel$ values between 2.8 and 4.2 [?]. Simulations on the NSTX upgrade spherical tokamak show that launching at high toroidal wave number appears to be an effective way to significantly reduce ion damping and thereby obtain large electron damping in the core [?]. To analyze coupling between the combline antenna and VEST plasma, J. G. Jo et al. used the finite element solver COMSOL and obtained maximum helicon wave coupling with $N_\parallel \sim 4.5$ at 500 MHz [?]. Recently, C. Lau et al. performed numerical studies with the full-wave code AORSA to understand the impact of SOL turbulence on helicon wave propagation and absorption in the DIII-D tokamak, finding that power loss in the SOL peaked at higher fluctuation wavelengths λ_{fluct} for high $N_\parallel$ [?]. These results demonstrate that helicon wave heating and current drive depend strongly on the launched $N_\parallel$ spectrum of the antenna, with different fusion devices and antennas requiring different optimized parameters for $N_\parallel$.

EXL-50 is a new spherical tokamak designed in 2018 and constructed in 2019. In 2023, it was upgraded to EXL-50U with a major radius of 0.6-0.8 m and a minor radius of 0.32-0.5 m. The primary objectives of the EXL-50U device are to achieve plasma currents I_p of 300-600 kA and to ensure that the ion temperature in the plasma core exceeds the electron temperature, with a target ratio of $T_i/T_e = 1.5$ [?]. Recently, it has achieved $I_p \sim 300\,\mathrm{kA}$ with a 1-second flat-top. To meet these experimental objectives, further research on wave heating and current drive capabilities in EXL-50U is needed.

A helical TWA consists primarily of an antenna box, feed, Faraday shield, and helical line. Its structure affects the $N_\parallel$ power spectrum, leading to the generation of sidebands [?]. Many previous studies have focused on the effects of the main peak of the antenna power spectrum on helicon wave heating and current drive. However, few have considered the influence of TWA power spectrum sidebands on helicon waves and current drive. Commercial software COMSOL can handle 3D RF antenna structures with dielectric medium or plasma loading and obtain the power spectrum by solving Maxwell' s equations [?]. The validity and correctness of RF antenna simulations based on COMSOL have been demonstrated by several codes [?].

Using EXL-50U experimental parameters, KSTAR-like traveling wave antennas are designed with COMSOL. By coupling the antenna power spectrum with GENRAY, we have studied the influence of sidebands from two KSTAR-like TWAs on HCD in EXL-50U plasma. The structure of this paper is as follows. In Section II, we briefly describe the models and equations governing helicon physics in EXL-50U plasma. Section III presents a broad parametric scan of parallel refractive index, frequency, density, temperature, and magnetic field for HCD. Section IV discusses a possible physical mechanism for the influence of sidebands on HCD. Section V presents the conclusions.

II. MODELS AND EQUATIONS

The propagation characteristics of helicon waves in plasma can be adequately described by a cold plasma dispersion relation, where the perpendicular refractive index $N_\perp$ in the plasma satisfies [?]:

$$(S+P)(S-N_{\parallel}^2)-\sqrt{[(S+P)(S-N_{\parallel}^2)-D^2]^2+4N_{\parallel}^2D^2P^2}$$

where S, D, and P are elements of the cold dielectric tensor in Stix's formulation [?], and $N_{\parallel}$ is the parallel refractive index.

Equation (1) reveals two distinct wave branches. The first, corresponding to the minus sign, is the fast wave (also known as the helicon wave); the second, with the plus sign, is the slow wave. The condition for helicon wave or slow wave propagation in plasma is $N_{\perp+}^2 > 0$ or $N_{\perp-}^2 > 0$, respectively. If the helicon wave frequency is f, the wavelengths of the helicon fast wave and slow wave can be expressed as $\lambda_+^{-1} = (N_{\perp+}) \times f/c$ and $\lambda_-^{-1} = (N_{\perp-}) \times f/c$, respectively.

According to [?], the critical parallel refractive index N_{acc} that separates the two branches can be estimated by:

$$N_{acc} > \sqrt{|P|}$$

which represents the accessibility condition. It is well known that the dominant damping mechanisms for helicon waves are electron Landau damping and transit-time magnetic damping [?]. When the wave phase velocity becomes comparable to the particle thermal velocity (i.e., $\omega/k_{\parallel} = v_{th}$), strong Landau damping occurs between the wave and particles. The sufficient condition for electron Landau damping absorption is $\omega/k_{\parallel} \leq 2.5v_{th}$ or that the parallel refractive index satisfies [?]:

$$N_{damp} \geq \frac{6.8}{\sqrt{T_e(\mathrm{keV})}}$$

Helicon wavelengths in EXL-50U plasma are much smaller than the machine dimensions. Due to this short-wavelength nature, the ray-tracing technique provides a good approximation for calculating HCD in EXL-50U plasma. GENRAY offers several options for power absorption and current drive. The Chiu model is used for electron and ion absorption, where the code calculates the vertical component of the imaginary part of the refractive index, while the standard Ehst-Karney model is employed for current drive [?].

The density and temperature profiles can be expressed using the following empirical formulas [?]:

$$n_e = (n_{ec} - n_{ea})[1-(r/a)^i]^s + n_{ea}$$

$$T_e = (T_{ec} - T_{ea})[1-(r/a)^i]^s + T_{ea}$$

In these expressions, n_{ea} and n_{ec} represent the edge and central electron densities, respectively, while T_{ec} and T_{ea} denote the central and edge electron temperatures, respectively, with $i = 1$ and $s = 1/2$. In the following calculations, we maintain constant temperature and density distributions, using only the central temperature and density to represent overall variations.

III. NUMERICAL RESULTS

A. Influence of Parallel Refractive Index, Frequency, Density, and Temperature on Helicon Wave Driven Current

The double-null equilibrium configuration of the EXL-50U device was reconstructed using the EFIT program Figure 1: see original paper. The density and temperature profiles are shown in Figure 1: see original paper and Figure 1: see original paper. The central toroidal magnetic field, electron density, and electron temperature are 0.757 T, $6 \times 10^{18}\,\mathrm{m}^{-3}$, and 1 keV, respectively. Thirty rays are launched from the low-field side with a Gaussian-like spectrum (denoted Step-G), and the total injection power is 1 MW. The power spectrum is expressed as $P = (\sin(N_\parallel - N_{\parallel 0})/(N_\parallel - N_{\parallel 0}))^2$, where $N_{\parallel 0}$ is the main peak of $N_\parallel$.

[Figure 2: see original paper] presents the relationships between driven current, parallel refractive indices $N_\parallel$, and frequency for $n_{ec} = 6 \times 10^{18}\,\mathrm{m}^{-3}$ and $T_{ec} = 1\,\mathrm{keV}$. Since the equilibrium magnetic field is in the counterclockwise direction, negative values are assigned to $N_\parallel$ in the simulations to produce positive driven current. The results show that when the frequency ranges from 300 MHz to 500 MHz, the helicon-driven current first increases and then decreases, peaking around $N_\parallel = 3 - 3.4$ at frequencies of 400-500 MHz. Therefore, for the engineering design of the helicon system on EXL-50U, $N_\parallel$ should be set around -3.2 to obtain higher drive current when the frequency exceeds 400 MHz.

[Figure 3: see original paper] shows the helicon wave propagation domain and wavelengths in the EXL-50U plasma density-magnetic field strength plane at $f = 476\,\mathrm{MHz}$. The region bounded by two thick black lines represents the transparent region for helicon waves where $N_{\perp -} > 0$. The threshold densities for helicon wave excitation gradually increase with magnetic field Figure 3: see original paper. The wavelength decreases with increasing density and increases with increasing magnetic field Figure 3: see original paper. When the magnetic field varies between 0.3-0.757 T, the densities for helicon wave propagation range from $4.2 \times 10^{18}\,\mathrm{m}^{-3}$ to $2.69 \times 10^{19}\,\mathrm{m}^{-3}$, and the wavelengths are less than 0.08 m.

[Figure 4: see original paper] illustrates the relationships between driven current, electron density, and temperature at $f = 476\,\mathrm{MHz}$ and $N_\parallel = -3.2$. Simulation results demonstrate that the driven current exhibits a relatively stable upward trend with increasing plasma temperature but shows an overall decrease with increasing density. Notably, helicon waves can drive substantial current at lower densities. For instance, at a density of $5.4 \times 10^{18}\,\mathrm{m}^{-3}$, a 1 MW helicon wave can drive approximately 500 kA of current with $T_{ec} = 1.1\,\text{keV}$, and the corresponding dimensionless efficiency is $\zeta \equiv e^3 P_{KT} \equiv 33 n_{20} I_{ARm} = 0.53$, which remains notably significant compared to the high current drive efficiency $\zeta = 0.64$ observed in previous DIII-D tokamak experiments.

B. Effect of Spectrum Sidebands on Helicon Wave Current Drive

Based on the simulation results presented above, it is evident that relatively higher helicon wave drive current is achieved when the frequency and $|N_\parallel|$ range from 400-500 MHz and 3-3.4, respectively. Next, two sets of KSTAR-like [11] helical traveling wave antennas are designed using COMSOL, labeled A and B, with a spectral peak of $N_\parallel = -3.2$ and a frequency of 476 MHz [Figure 5: see original paper] and [Figure 6: see original paper].

Antennas A and B have ten and six current bands, respectively. The spacing between adjacent current bands is equal and denoted as D. For a single turn of the helical line, the dimensions L_1, L_2, and D for antennas A and B are 270 mm, 146 mm, 52 mm and 270 mm, 140 mm, 52 mm, respectively.

[Figure 6: see original paper] shows the radiation power spectra of the KSTAR-like helical traveling wave antennas A (Step-A) and B (Step-B), along with a Gaussian-like spectrum (Step-G). The parallel refractive indices corresponding to the main peaks (position 1) of these three spectra are all $N_{\parallel 1} = -3.2$. The primary difference among these spectra lies in the intensity and number of sidebands. Both Step-A and Step-B spectra have secondary peaks (position 2) with relatively high energy, whose parallel refractive indices are $N_{\parallel 2} = 8.6$. The term "spectral width" refers to the width between two points where the power spectrum intensity is half of its maximum. The spectral width of the main peak follows the order: Step-A < Step-B < Step-G, and the spectral width of the secondary peak in Step-A is smaller than that in Step-B.

To study the influence of sidebands on HCD, the antenna spectrum is coupled with the GENRAY program. In [Figure 7: see original paper], a total of 30 rays are emitted from the low-field side with an injection power of 1 MW, and the energy spectrum of the 30 rays is a fitting function of the antenna radiation spectrum at $t = 0$. [Figure 8: see original paper] and [Figure 9: see original paper] depict the relationships between the driven currents of Step-A, Step-B, and Step-G, and density and temperature. ΔI_{AG} and ΔI_{BG} represent the driven current differences between Step-A and Step-G and between Step-B and Step-G, respectively, with their maximum values denoted as $\Delta I_{\text{max-AG}}$ and $\Delta I_{\text{max-BG}}$. The simulations indicate that when the magnetic field (with central magnetic field B_0) remains constant, within specified temperature (0.6-1.4 keV) and density ($4.2 \times 10^{18}\,\text{m}^{-3} - 1.2 \times 10^{19}\,\text{m}^{-3}$) ranges, the impact of sidebands on HCD intensifies as temperature increases [Figure 8: see original paper] and [Figure 9: see original paper]. In some density cases, the impact of sidebands on HCD cannot be ignored. For example, at typical density values, when $n_{ec} = 7.8 \times 10^{18}\,\text{m}^{-3}$, the influence of sidebands on HCD increases significantly.

Maximum differences $\Delta I_{\text{max-AG}}$ and $\Delta I_{\text{max-BG}}$ reach 91.281 kA and 87.137 kA, respectively, while minimum values are -49.355 kA and -44.034 kA as shown in [Figure 9: see original paper]. Additionally, when increasing the operating density of the device, special attention should be paid to the impact of sidebands on HCD. As shown in [Figure 9: see original paper], when $n_{ec} = 1.2 \times 10^{19}\,\text{m}^{-3}$, the impact of sidebands on HCD is particularly large, with maximum differences $\Delta I_{\text{max-AG}}$ and $\Delta I_{\text{max-BG}}$ reaching 67.232 kA and 73.308 kA, respectively. In the green and dark green areas of [Figure 9: see original paper], the driven currents of Step-A and Step-B are greater than that of the Gaussian-like spectrum Step-G, and the driven current of Step-A is slightly larger than that of Step-B. This implies that to achieve relatively high driven current, the spectral width should not be too broad.

[Figure 10: see original paper] presents the influence of magnetic field on HCD under four density-temperature conditions. Simulation results indicate that in low-density plasma ($n_{ec} = 4.2 \times 10^{18}\,\text{m}^{-3}$), when the central magnetic field is below 1.3 T, the influence of sidebands on helicon wave current drive is minimal. However, when the central magnetic field exceeds 1.3 T, the impact of sidebands on current drive increases (shown in Figure 10: see original paper and (b)). The trend is opposite in medium-density plasma ($n_{ec} = 7.8 \times 10^{18}\,\text{m}^{-3}$), where the influence of sidebands on HCD is small when the central magnetic field is above 1.3 T and increases when it is below 1.3 T (shown in Figure 10: see original paper and (d)). Increased temperature enhances the impact of sidebands on HCD to some extent. As temperature rises, the impact of sidebands on HCD intensifies. For example, when $n_{ec} = 4.2 \times 10^{18}\,\text{m}^{-3}$, as temperature increases from 0.7 keV to 1.2 keV, the difference in driving current for Step-A, Step-B, and Step-G becomes pronounced, with $|\Delta I_{\text{max-AG}}|$ and $|\Delta I_{\text{max-BG}}|$ increasing from 61 kA and 57 kA to 72 kA and 75 kA, respectively (as shown in Figure 10: see original paper and (b)). When $n_{ec} = 7.8 \times 10^{18}\,\text{m}^{-3}$, the difference in driving current for Step-A, Step-B, and Step-G is more pronounced, with $\Delta I_{\text{max-AG}}$ and $\Delta I_{\text{max-BG}}$ increasing from 112 kA and 104 kA to 178 kA and 166 kA, respectively (as shown in Figure 10: see original paper and (d)).

[Figure 11: see original paper] shows the relationships between the driven current differences ΔI_{AG} and ΔI_{BG}, density, and magnetic field when $T_{ec} = 1.4\,\text{keV}$ remains constant. In medium-density/low-magnetic-field plasma and relatively low-density/high-magnetic-field plasma, the influence of sidebands on HCD intensifies. The largest differences $\Delta I_{\text{max-AG}}$ and $\Delta I_{\text{max-BG}}$ reach 177.820 kA and 165.178 kA, respectively, in the deep green region of [Figure 11: see original paper], and -165.741 kA and -123.675 kA in the yellow region.

[Figure 12: see original paper] shows the drive current profiles of Step-A, Step-B, and Step-G. Case 1 parameters are $n_{ec} = 4.2 \times 10^{18}\,\text{m}^{-3}$, $T_{ec} = 0.7\,\text{keV}$, $B = 2.25B_0$. Case 2 parameters are $n_{ec} = 7.8 \times 10^{18}\,\text{m}^{-3}$, $T_{ec} = 0.9\,\text{keV}$, $B = 1B_0$. The simulation results indicate that under specific conditions, the sidebands of Step-A and Step-B influence not only the magnitude of HCD but also the profile of the driven current, causing the current peak to shift toward the center or edge (see [Figure 12: see original paper]). For example, when the antenna spectrum changes from Step-G to Step-A, the current peak shifts from a normalized radius of 0.32 to 0.13 for Case 1 (Figure 12: see original paper), and from 0.1075 to 0.1225 for Case 2 (Figure 12: see original paper). The current peak positions of Step-A and Step-B are close to each other, but Step-B' s current distribution disperses more toward the edge, resulting in a lower driven current peak compared to Step-A, indicating poorer locality (Figure 12: see original paper). This suggests that under certain conditions, an antenna spectrum with narrow sidebands can not only enhance the driven current to some extent but also increase the locality of the current distribution, which is beneficial for local control.

IV. DISCUSSION

To reveal the physical mechanism underlying the influence of sidebands on HCD, this paper next simulates the current profiles of two rays, their trajectories in the poloidal cross-section, and the variations of the Landau refractive index N_{damp}, accessibility condition N_{acc}, and parallel refractive index $N_{\parallel}$ along the propagation distance for Case 1 and Case 2 ([Figure 13: see original paper]-[Figure 15: see original paper]). These two rays correspond to the main peak and secondary peak of Step-A and Step-B, with $N_{\parallel 1} = -3.2$ and $N_{\parallel 2} = 8.6$, respectively. The simulations show that as the two rays propagate in the plasma, their lower limits meet the accessibility condition, and $N_{\parallel}$ gradually shifts upward as the propagation distance increases. The parallel refractive index $N_{\parallel 2}$ is close to N_{damp}, enabling the ray to meet the strong Landau damping condition over a short propagation distance and deposit quickly near the core (Figure 14: see original paper and (d), Figure 15: see original paper and (d)). Due to the significant difference between $N_{\parallel 1}$ and N_{damp}, the ray travels a relatively long distance before depositing into the plasma. When plasma parameters change from Case 1 to Case 2, the drive current peak of the ray with $N_{\parallel 1} = -3.2$ changes from 255 A/cm^2 to 555 A/cm^2, and its position moves from normalized minor radius 0.31 to 0.07 ([Figure 13: see original paper]). The driven current profile of the $N_{\parallel 2} = 8.6$ ray is less sensitive to plasma parameters than that of the $N_{\parallel 1} = -3.2$ ray, showing a single peak in the current with minor changes in radial distribution range (at normalized minor radius 0.24-0.27), effectively maintaining locality. The driven current magnitude of the $N_{\parallel 2} = 8.6$ ray is smaller than that of the $N_{\parallel 1} = -3.2$ ray ([Figure 13: see original paper]).

From the dispersion relation Eq. (1) and [Figure 14: see original paper] and [Figure 15: see original paper], it is evident that plasma parameters such as magnetic field and density affect the upward or downward shift of $N_{\parallel}$ in the plasma. The shorter the ray propagation distance, the smaller the influence of plasma parameters on the upward or downward shift of $N_{\parallel}$. The ray with $N_{\parallel 1} = -3.2$, being far from the strong damping condition, propagates over a considerable distance before being absorbed by the plasma. Consequently, the parallel refractive index undergoes multiple shifts, making the effect of the driven current more sensitive to plasma parameters. In contrast, the strongly damped ray with $N_{\parallel 2} = 8.6$ is absorbed over a short propagation distance, so the upward or downward shift of the parallel refractive index is less affected by plasma parameters, leading to the generation of a stable and strongly localized driven current profile.

From the above analysis, it can be seen that one of the important factors affecting HCD under different parameters is the main peak of the antenna spectrum. Due to the stability and locality of the current driven by rays satisfying the strong damping condition, the presence of certain sidebands close to the strong Landau damping condition in the antenna spectrum may be beneficial for HCD, potentially improving the driven current magnitude and enhancing current localization control under certain conditions.

V. SUMMARY

This study investigates the influence of sidebands in the spectra of two KSTAR-like helical TWAs on HCD in the EXL-50U spherical torus plasma. First, under certain conditions, the effects of parallel refractive index, frequency, temperature, and density on HCD are analyzed. It is found that when frequency, $|N_\parallel|$, temperature, and density satisfy $300\,\mathrm{MHz} \leq f \leq 500\,\mathrm{MHz}$, $3 \leq |N_\parallel| \leq 3.4$, $0.7\,\mathrm{keV} \leq T_{ec} \leq 1.3\,\mathrm{keV}$, and $5.4 \times 10^{18}\,\mathrm{m}^{-3} \leq n_{ec} \leq 7.8 \times 10^{18}\,\mathrm{m}^{-3}$, respectively, helicon waves can achieve relatively high driven current in EXL-50U plasma, approximately 200-600 kA.

Next, based on these results, two sets of 476 MHz KSTAR-like TWAs are designed for EXL-50U using COMSOL. Their spectra have the same $N_\parallel = -3.2$ corresponding to the main peak but different sidebands. By coupling their spectra with GENRAY and comparing HCD driven by them with that driven by a Gaussian-like spectrum, the influence of sidebands from the two KSTAR-like TWAs on HCD in EXL-50U plasma has been studied. When central temperature, density, and magnetic field strength vary within the ranges of $0.6\,\mathrm{keV} \leq T_{ec} \leq 1.4\,\mathrm{keV}$, $4.2 \times 10^{18}\,\mathrm{m}^{-3} \leq n_{ec} \leq 1.2 \times 10^{19}\,\mathrm{m}^{-3}$, and $0.4542\,\mathrm{T} \leq B \leq 2.082\,\mathrm{T}$, respectively, the simulation results indicate:

1) Under medium-density/low-magnetic-field and low-density/high-magnetic-field conditions, the influence of sidebands on HCD is significant, with the largest difference in driven current among these three spectra reaching 178 kA under the same injection power.

2) Under certain conditions, higher temperature leads to greater impact of spectral sidebands on HCD.

3) The sidebands not only affect the magnitude of HCD but also cause the current peak to shift toward the center or edge ([Figure 12: see original paper]). Narrow sidebands with parallel refractive index close to the strong Landau damping condition may improve the driven current magnitude and localized control, which may be beneficial for HCD.

Finally, the physical mechanism of the influence of sidebands on HCD is discussed: plasma parameters such as magnetic field and density affect the upward or downward shift of $N_{\parallel}$ in the plasma. The shorter the ray propagation distance, the smaller the influence of plasma parameters on the upward or downward shift of $N_{\parallel}$. Rays close to the strong damping condition are absorbed over a short distance, resulting in their parallel refractive index being less affected by plasma parameters and achieving stable and strongly localized HCD. Consequently, under certain conditions, if the antenna spectrum has narrow sidebands with parallel refractive index close to the strong Landau damping condition, it may be beneficial for improving driven current magnitude and local control. This research provides guidance for the design of RF antennas and HCD experiments.

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