Three-Dimensional Modeling and Comparison of Ion Cyclotron Wave Propagation and Heating in EAST

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Abstract

The effects of multiple-pass absorption assumption and single-pass absorption assumption on the propagation and power deposition of minority ion heating waves launched by the EAST four-strap antenna were investigated using finite element method and hot dielectric tensor simulations. The simulation results demonstrate that under otherwise identical conditions, the electric field distributions near the antenna calculated by the two models are essentially consistent when the antenna current phases are $(0\ 0\ \pi\ \pi)$ and $(0\ \pi\ \pi\ 0)$; however, significant differences emerge between the two models' electric field simulation results when the antenna current phase is $(0\ \pi\ 0\ \pi)$. Ion cyclotron waves propagating multiple toroidal turns represent the primary cause of these discrepancies. In toroidal fusion devices, simulation results based on the single-pass absorption assumption are underestimated when the parallel wavenumber of the wave is large. For toroidal fusion devices, the applicability of the single-pass absorption assumption necessitates further systematic investigation.

Full Text

Construction and Comparison of 3D EAST Ion Cyclotron Wave Propagation and Heating Models

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Abstract

This study employs the finite element method and hot dielectric tensor to investigate the effects of non-single-pass absorption and single-pass absorption assumptions on wave propagation and power deposition for minority ion heating using the EAST four-strap antenna. Simulation results demonstrate that under identical parameters, the electric field distributions near the antenna calculated by both models are essentially consistent for antenna current phases of $(0\ 0\ \pi\ \pi)$ and $(0\ \pi\ \pi\ 0)$. However, significant differences emerge between the two models when the antenna current phase is $(0\ \pi\ 0\ \pi)$. The primary cause of this discrepancy is ion cyclotron waves that propagate multiple toroidal turns. In toroidal fusion devices, when the parallel wave number is large, simulations based on the single-pass absorption assumption yield underestimated results. The applicability of the single-pass absorption assumption in toroidal fusion devices requires further systematic investigation.

Keywords: Ion cyclotron wave, Minority H ion heating, Power deposition, Hot dielectric tensor, Perfectly matched layer
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Ion cyclotron resonance heating (ICRH) represents one of the primary auxiliary heating methods employed in most stellarators and tokamaks [1,2]. For large or open plasma domains, ICRH codes typically utilize absorbing boundary conditions to truncate the computational domain—an approach also known as the single-pass absorption assumption. Common absorbing boundary conditions include radiation boundaries [3], perfectly matched layers (PML) [4], and unidirectional approximations of the wave equation [5]. Lamalle et al. [6] developed an initial ICRH coupling code that replaced plasma with seawater medium and employed PML to reduce reflected wave effects. Jacquot et al. [7] developed a slab coupling code for ICRH that used PML to simulate core plasma absorption of ion cyclotron waves. Shiraiwa et al. [8] developed an ICRH heating code for the WEST device, which reproduced the antenna and part of the vacuum vessel structure while implementing radiation boundaries at both ends of the vacuum vessel.

In fusion devices, the single-pass absorption assumption implies that waves will be completely absorbed by the plasma before completing one full propagation cycle around the vacuum chamber. However, the applicability of this assumption in fusion devices lacks systematic investigation. Based on COMSOL software, this study develops both a non-single-pass absorption assumption model for the full EAST vacuum chamber and a single-pass absorption assumption model for a 1/4 EAST vacuum chamber. The propagation and power deposition of ion cyclotron waves during minority ion heating in D(H) plasma are comparatively studied under three antenna current phasings: ($0\ \pi\ 0\ \pi$), ($0\ 0\ \pi\ \pi$), and ($0\ \pi\ \pi\ 0$).

1.1 EAST 3D Full-Vacuum-Chamber ICRH Code

The structural schematic of the EAST 3D full-vacuum-chamber domain ion cyclotron heating code and the 2D cross-section of the EAST vacuum chamber are shown in [Figure 1: see original paper]. The main vacuum chamber exhibits toroidal symmetry about the z-axis, with its structure referencing the currently employed first-wall configuration featuring a lower tungsten divertor. The ion cyclotron antenna is positioned approximately 2.4 m in the positive x-direction. The single-pass absorption assumption is not employed in this model.

The ion cyclotron antenna structure references the EAST I-port four-strap ICRH antenna, illustrated in [Figure 2: see original paper]. In Figure 2(a), current straps, Faraday screens, and the antenna box are marked in red, gray, and orange, respectively. The poloidal curvature radius is approximately 760 mm, and the toroidal curvature radius is about 1980 mm. Three partitions are installed in the middle of the antenna box to avoid coupling between straps. The back of the antenna box features four vacuum transmission line (VTL) interfaces, with four transmission lines connecting to four current straps [FIGURE:2(b)]. All strap corners employ a uniform fillet design with a radius of 30 mm, and hollow structures are adopted to enhance heat dissipation. Both antenna and antenna box materials are designated as 316L steel, modeled as impedance boundaries with thermal losses. Limiter structures are not currently included in the antenna configuration.

1.2 EAST 3D 1/4-Vacuum-Chamber ICRH Code

[Figure 3: see original paper] presents the structural schematic of the EAST 3D 1/4-vacuum-chamber ICRH code, where the gray region represents the vacuum chamber covering a toroidal angle range from $-\pi/4$ to $\pi/4$. Both ends of the vacuum chamber are PML regions (green areas). The PML can absorb electromagnetic waves entering this region without reflection, simulating an infinitely long vacuum chamber structure in the toroidal direction—i.e., single-pass absorption. The antenna structure is identical to that used in the full-vacuum-chamber ICRH code.

1.3 Plasma Parameter Configuration

When the EAST four-strap antenna interacts with plasma, the antenna's private region (blue area in Figure 1) is a vacuum, while the vacuum chamber interior is filled with plasma (gray area in Figure 1). Plasma density and temperature profiles adopt experimental data from EAST shot #107399 [Figure 4: see original paper]. The magnetic field uses a double-null configuration, with plasma heating achieved through lower hybrid wave (LHW), electron cyclotron resonance heating (ECRH), and ion cyclotron resonance heating (ICRH) [Figure 4: see original paper]. The EFIT and SOLPS codes are employed to reconstruct the magnetic field distribution [FIGURE:5(a)], density distribution [FIGURE:5(b)], electron temperature distribution [FIGURE:5(c)], and ion temperature distribution [FIGURE:5(d)] at t = 8 s for shot #107399. Minority hydrogen ion fundamental heating is applied in deuterium-hydrogen plasma with a hydrogen concentration of 10%. The antenna output power is 1 MW.

1.4 Plasma Modeling

The wave equation in magnetized plasma is:

$$\nabla \times \nabla \times \mathbf{E} - k_0^2 \, _r \cdot \mathbf{E} = -i\omega\mu_0 \mathbf{J}_{ant}$$

where $k_0 = \omega/c$ is the vacuum wavenumber, ϵ_0 is the vacuum permittivity, ω is the angular frequency, μ_0 is the vacuum permeability, and $_r$ is the relative dielectric tensor. When the external magnetic field is aligned with the z-axis, the equivalent relative dielectric tensor for hot plasma is expressed as [9]:

$$_r = \mathbf{I} + \sum_s \frac{\omega_{ps}^2}{\omega^2} \sum_{n=-\infty}^{\infty} \int d^{3v} \frac{e^{-b_s}}{k_\parallel v_\parallel - \omega + n\Omega_s} \times (...)$$

where n is the harmonic order, s denotes different particle species, I_n and I_n' are the nth-order modified Bessel function and its derivative, and $Z(\zeta_n)$ and $Z'(\zeta_n)$ are the plasma dispersion function and its derivative. The nth-order argument of the dispersion function is $\zeta_n = (\omega - n\Omega_s)/(k_\parallel v_{ths})$.

The EAST four-strap antenna primarily employs three current phasings: (0 0 π π), (0 π π 0), and (0 π 0 π). Their power spectrum peaks are located at $k_\parallel = 5$ rad/m, $k_\parallel = 8$ rad/m, and $k_\parallel = 13$ rad/m, respectively. At high plasma density, only the fast wave (FW) with $k_\parallel = 5$ rad/m propagates in the plasma. The magnitude of the fast wave' s wave vector component perpendicular to the magnetic field can be calculated from the dispersion relation [9]:

$$k_\perp^2 = \frac{(\epsilon_R - n_\parallel^2)(\epsilon_L - n_\parallel^2)}{\epsilon_S - n_\parallel^2}$$

The hot dielectric tensor incorporates fourth-order finite Larmor radius approximation, i.e., $n = [-4, 4]$ in equations (3)-(8). The tensor rotation method described in reference [10] is employed to rotate the magnetic axis direction in the hot dielectric tensor from the z-axis to the magnetic field line direction. Combined with the 3D magnetic field distribution, the 3D hot plasma dielectric tensor $_{hot}$ in the tokamak vacuum chamber is obtained. The power deposition of waves in plasma is calculated as:

$$P_{dep} = \frac{1}{2}\Re(\mathbf{J} \cdot \mathbf{E}^*) = \frac{1}{2}\omega\epsilon_0\Im(\mathbf{E}^* \cdot \ _{hot} \cdot \mathbf{E})$$

2.1 Electric Field Comparison Analysis

In this section, Case 1 represents the EAST 3D 1/4-vacuum-chamber ICRH code, while Case 2 represents the EAST full-vacuum-chamber ICRH code.

[Figure 6: see original paper]–[Figure 11: see original paper] compare the propagation of ion cyclotron waves in plasma simulated by the two codes under three phasing conditions. Figures 6(a)–11(a) show the electric field distributions in the x-y plane, while Figures 6(b)–11(b) display the electric field distributions in the x-z plane. Simulation results indicate that for current phasings of (0 0 π π) and (0 π π 0), the electric field distributions near the antenna are essentially consistent between the two cases. However, for the (0 π 0 π) phasing, significant differences emerge between the two cases' electric field simulations. The likely reason is that larger parallel wave numbers result in smaller angles between the wave propagation direction and the magnetic field direction (toroidal direction). Smaller angles enable ion cyclotron waves to propagate longer distances along the toroidal direction, with some waves circulating multiple times around the vacuum chamber (FIGURE:11(a)), violating the single-pass absorption assumption. The electric field near the antenna becomes a superposition of the launched wave and waves that have completed one or more toroidal transits, leading to different simulated electric field distributions between Case 1 and Case 2.

2.2 Power Deposition Analysis

presents the calculated total power deposition results in plasma for Case 1 and Case 2. The table shows that the relative error in power deposition between Case 1 and Case 2 does not exceed 2% for the same current phasing. This phenomenon indicates that while the single-pass absorption assumption degrades electric field predictions at large parallel wave numbers, it remains essentially valid for total power deposition predictions. Additionally, comparing total power deposition across different current phasings reveals that antenna-plasma coupling power decreases as $k_\parallel$ increases. The influence of current phasing on coupling power is consistent with experimental trends observed on EAST [11].

shows the proportion of electron power deposition in the vacuum chamber under different antenna current phasings. The data indicate that electron power deposition in both Case 1 and Case 2 increases with $k_\parallel$. The likely reason is that as $k_\parallel$ increases, electron damping of ion cyclotron waves intensifies, potentially indicating a larger power deposition region for ion cyclotron waves. The difference in electron power deposition fraction between Case 1 and Case 2 also increases with $k_\parallel$ under the same antenna current phasing, demonstrating that the single-pass absorption assumption affects particle power deposition fractions.

For the antenna current phasing of (0 π 0 π), [Figure 12: see original paper] and [Figure 13: see original paper] compare the power deposition distributions of electrons and hydrogen ions in the x-y plane between Case 1 and Case 2. Hydrogen ion power deposition is primarily distributed near the hydrogen ion cyclotron resonance layer, while electron power deposition is more concentrated in high-density, high-temperature plasma regions. Comparing the same 1/4 vacuum chamber region, both electron and hydrogen ion power deposition densities are significantly higher in Case 2. The probable cause is that ion cyclotron waves not satisfying the single-pass absorption assumption in Case 2 produce additional power deposition. These results demonstrate that toroidal geometry causes some antenna-launched ion cyclotron waves to return to the antenna vicinity, and under certain conditions, simulations based on the single-pass absorption assumption exhibit substantial errors.

Conclusion

Employing EAST experimental parameters, this study developed both a 3D 1/4-vacuum-chamber ICRH code based on the single-pass absorption assumption and a 3D full-vacuum-chamber ICRH code without this assumption. Both codes were used to simulate ion cyclotron wave propagation and power deposition during minority ion heating in D(H) plasma. Simulation results reveal that the non-single-pass absorption assumption incorporates the effects of ion cyclotron waves that have propagated one or more toroidal turns on electric field distribution. The proportion of ion cyclotron waves completing toroidal transits increases with parallel wave number. Waves not satisfying the single-pass absorption assumption significantly influence electric field distribution and particle power deposition patterns, though their impact on total power deposition remains small.

References

1. Bobkov V, Usoltceva M, Faugel H, et al. Development of pre-conceptual ITER-type ICRF antenna design for DEMO [J]. Nuclear Fusion, 2021, 61(4): 046039 046052.
2. Du D, Saito K, Kwak J G, et al. Design of an optimized load-resilient conjugate T for the ICRH system in the LHD using a novel hybrid circuit/3DLHDAP code and experimental results[J]. Nuclear Fusion, 2023, 63(12): 126027 126042.
3. Holland R. THREDE: A Free-Field EMP Coupling and Scattering Code[J]. Nuclear Science IEEE Transactions on, 1977, 24(6): 2416 2421.
4. Berenger J P. A perfectly matched layer for the absorption of electromagnetic waves[J]. Physics of Plasmas, 1994, 114(2): 185 200.

5. Higdon R L. Absorbing Boundary Conditions for Difference Approximations to the Multi-Dimensional Wave Equation[J]. Mathematics of Computation, 1986, 47(176): 437 459.

6. Lamalle P U, Messiaen A M, Dumortier P, et al. recent developments in icrf antenna modelling[J]. NUCLEAR FUSION, 2006, 46: 432–443.

7. Jacquot J, Colas L, Clairet F, et al. 2D and 3D modeling of wave propagation in cold magnetized plasma near the Tore Supra ICRH antenna relying on the perfecly matched layer technique[J]. Plasma Physics and Controlled Fusion, 2013, 55(11): 115004 115020.

8. Shiraiwa S, Bertelli N, Tierens W, et al. Magnetic potential based formulation for linear and non-linear 3D RF sheath simulation[J]. Nuclear Fusion, 2023, 63: 026024 026035.

9. Vallejos P, Johnson T, Ragona R, et al. Effect of poloidal phasing on ion cyclotron resonance heating power absorption[J]. Nuclear Fusion, 2019, 59(7): 076022 076036.

10. Jaeger E F, Berry L A, D' azevedo E, et al. All-orders spectral calculation of radio-frequency heating in two-dimensional toroidal plasmas[J]. Physics of Plasmas, 2001, 8(5): 1573 1583.

11. Yang Y, Xinjunzhao, Yanpingqin, et al. Recent ICRF coupling experiments on EAST[J]. Plasma Science & Technology, 2018, 20(4): 045102 045106.

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Note: Figure translations are in progress. See original paper for figures.