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Energy, momentum and particle balances of electrons in lower hybrid wave sustained plasmas on the TST-2 spherical tokamak

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In the TST-2 spherical tokamak (ST), non-inductive start-up by lower-hybrid waves (200 MHz) has been studied and a plasma current of 27 kA was achieved [1]. However, further study is necessary to optimize the current drive [2]. An electron transport model is constructed to simulate electron diffusion in 2-dimensional phase space, and an X-ray emission model is constructed to simulate X-ray emissions. Comparison with experimental data shows that a major part of the LHW deposition power is lost by fast electrons hitting the outboard limiter, while a minor part is used to heat cold bulk electrons. The diffusion in real space is well described by the RF induced radial transport, which is often used to interpret fast ion diffusion in ICRF heating [3]. The present work clearly demonstrates the RF induced transport of fast electrons for the first time. In addition, this result implies that there is an appropriate density range and that the outboard power deposition is preferable.

Figure 1 shows the schematic configuration of the electron transport model. Electrons starting from a magnetic surface defined by $R_{\rm sin}$ and $R_{\rm sout}$ are accelerated or decelerated by the electric field of the lower-hybrid wave (LHW). Here we assume, the acceleration or deceleration occurs only at the inboard side, because the inboard power deposition is expected from ray traces [4] and electrons would spend longer time at the inboard side than at the outboard side due to the low aspect ratio configuration. As the co-directed parallel velocity increases by LHW, the orbit expands outward. The velocity would be slowed down through collisions with cold bulk electrons or ions or neutral molecules, and they are assumed to occur at both inboard and outboard midplane striking points ($R_{\rm in}$ and $R_{\rm out}$).

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The inboard velocity kick $R_{\rm sin}$ during a time step $R_{\rm sout}$ is represented by the summation of a random walk due to LHW and the collisional slowing down:
$R_{\rm sout}$
where $R = 0.585\ \mathrm{m}$ is the inboard random kick with a Gaussian distribution function, and $\delta R_{\rm out}$ is the total collision frequency. The statistical average $R_{\rm LCFS}$ represents the diffusion coefficient in velocity space, and it is a function of $V_{||}$ (Fig. 2(a)). We adjust the shape to reproduce the experimental parameters described later.

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To simplify the model, we neglect the perpendicular velocity and use the conservation of canonical angular momentum. Then a change in Δt becomes a function of inboard velocity kick $\Delta V_{||} = \tilde{V}_{||} - \nu_{||} V_{||} \Delta t, \quad (1)$:
$\tilde{V}_{||}$
Using several additional approximations, the increment $\nu_{||}$ is written as

$$\left\langle \tilde{V}_{||}^2 / \Delta t \right\rangle$$

where $V_{||}$ is the electron cyclotron frequency for a given poloidal magnetic field $\left\langle \tilde{V_{||}}^{2} \right\rangle^{1/2}$. The effect on $f(V_{||})dV_{||}$ by the collisions at $R_{\rm sout}$ can be written by a similar equation.

By tracing many electrons we obtain the velocity ($R_{\rm sout}$) distribution function and the real space distribution functions. Equations (1) and (3) indicate that the velocity space diffusion induces real space diffusion. This is what we call RF induced transport. When the electrons reach the outboard limiter, they are lost and new cold electrons at $\Delta t = 5 \times 10^{-7}\ \mathrm{s}$ (and $V_{\rm loss}$) are supplied by electron impact ionization of neutrals. The density of neutral is adjusted to preserve the number of electrons. Steady state velocity and real space distributions are obtained after a sufficient time (Fig. 2(b)), and we can calculate energy, momentum (i.e., current) and particle flow.

The model parameters, such as the velocity random walk step and the initial starting positions R_{out}, $\Delta V_{||}$, are adjusted to reproduce the following experimental parameters: LHW injection power: 60 kW, electron density: $m_e\left(R_{\mathrm{in}}-R_{\mathrm{out}}\right)\Delta V_{||} = \left(m_e V_{||}-eR_{\mathrm{out}}B_p\right)\Delta R_{\mathrm{out}}$. (2), plasma current: 17 kA and the experimental hard X-ray emission shown later. From the model parameters and Eq. (3), we can also estimate the typical velocity ΔR_{out} ($\Delta R_{\mathrm{out}} = \Delta V_{||}\left(R_{\mathrm{sout}}-R_{\mathrm{sin}}\right)/R_{\mathrm{out}}/\Omega_{\mathrm{pe}}$, (3)) of the fast electrons hitting the outboard limiter (see Fig. 2(b)). Analysis of the obtained state reveals that about 44-49 kW is lost by the escaping electrons and about 6-10 kW is used for bulk electron heating, which is consistent with the measured bulk electron temperature (Ω_{pe}) when we assume ITER IPB98(y,2) scaling for the energy confinement time. The obtained neutral density and particle confinement time for the fast electrons are reasonable.

The most critical test of the model is the comparison of the energy of fast electrons which hit the limiter, because the typical energy B_p is a function of ΔR_{in}, and it can be approximated by the distance between the outboard limiter position and the outboard last closed flux surface position R_{out}, we compared the hard X-ray spectra for two discharges with different $V_{||}$s (Case I and Case II in Fig. 3). Since we do not know the exact R_{sout}s, we assume the difference between R_{sin}s in Case I and II are the same as those (30 mm) between the experimental R_{sin}s. The X-ray spectrum from a molybdenum limiter for a given energy distribution of lost electrons is calculated using the method described in [5], but there are several ambiguities, and we cannot compare the absolute emission levels between the calculations and the measurements. Case I and II show a large difference in the spectral shape and the difference is well characterized by different R_{sout}.

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These results indicate that a higher density is preferable from the viewpoint of transport, because it suppresses the outward shift of electron orbits. In addition, outboard RF power deposition is preferable than the inboard deposition, because the outboard acceleration causes shift of $2\times10^{17}\ \mathrm{m}^{-3}$ toward the magnetic axis (see Fig. 1).

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