Simulation study of electron cyclotron current drive in helical plasmas

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Abstract

• Electron cyclotron current drive (ECCD) is one of the reliable methods to drive the plasma current. ECCD can control current profile locally and has been applied for toroidal devices to keep the current profile, to stabilize MHD instabilities and to cancel the bootstrap current in helical systems[1].

• In order to study the ECCD physics in helical plasmas, we study effects of the trapped particle on ECCD and analyze the contribution of Fisch-Boozer effect and Ohkawa effect.

• We simulate ECCD in Heliotron-J by using GNET code which can evaluate steady state solution of distribution function in 5-D phase space (3-D space and 2-D velocity space) [2].

• Electron cyclotron heating is taken into account through quasi linear heating term. In this study, we modify the heating term to the realistic one.

• We improve the GNET code to conserve the momentum in order to simulate the current drive. We present the development process of this operator and simulation results.

Physics of ECH and ECCD

ECH(Electron Cyclotron Heating)

• The electrons satisfying the electron cyclotron resonance condition,

$$\omega = \ell\Omega_e/\gamma + k_\parallel v_\parallel$$

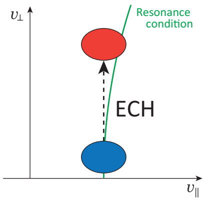
are selectively accelerated[3,4].

ω : Frequency of EC wave

$k_\parallel$: Wave vector parallel to ***B***

Ω_e : Electron cyclotron frequency

• Electron energy perpendicular to magnetic field is increased.



ECCD(Electron Cyclotron Current Drive)

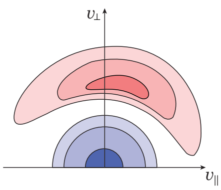
Fisch-Boozer Effect

• The anisotropic velocity distribution by ECH relaxes to isotropic one through the collisional process.

• The collision frequency is proportional to v^{-3}.

• The relaxation of the accelerated electrons is more slowly.

• As a result the current is driven in a negative $v_\parallel$ direction .

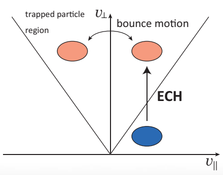


Ohkawa Effect

• Electrons in the trapped particle region form symmetric distribution rapidly through bounce motions.

• Asymmetric distribution in the low energy region due to the deficit contributes to the current drive.

• As a result current is driven in the positive $v_\parallel$ direction (opposite to Fisch-Boozer effect).



Experiment of ECCD in Heliotron-J

Control of non-inductive current in Heliotron J, G. Motojima, *et al* Nucl. Fusion 47 (2007)[5]

• EC current is evaluated in the three magnetic configurations.

• $\varepsilon_b = B_{04}/B_{00}$: bumpiness

• ε_b=0.01 : low bumpiness

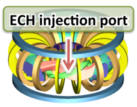
EC power deposits on the ripple top. Little trapped electron is generated by ECH. → **Fisch-Boozer effect is expected.**

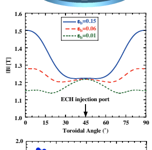
• ε_b=0.15 : high bumpiness

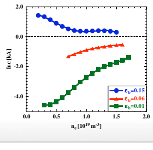
Trapped particle region is wide. Many trapped electrons are generated by ECH. → **Ohkawa effect is expected.**

• The current values decrease as the electron density increases.

• The direction of EC current reverses between high and low bumpiness magnetic configurations.







Simulation model

• GNET code can solve the linealized drift kinetic equation as a initial value problem based on the Monte Carlo technique in 5-D phase space and evaluate steady state solutions ($t = \infty$).

$$\frac{\partial \delta f}{\partial t} + (\boldsymbol{v}_d + \boldsymbol{v}_\parallel)\cdot\frac{\partial \delta f}{\partial \boldsymbol{x}} + \dot{\boldsymbol{v}}\cdot\frac{\partial \delta f}{\partial \boldsymbol{v}} - C^{\rm coll}(\delta f) = S^{\rm ql}(f_{\rm Max})$$

$C^{\rm coll}$: Collision operator, $S^{\rm ql}$: Source term

• We follow the test particle orbit to obtain the steady state solution of the distribution function δf.

• The collisional effects are taken into account using the linear Monte Carlo collision operator (Boozer and Kuo model).

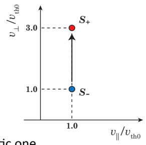
$$C^{\rm coll}(\delta f) = \underbrace{\frac{1}{v^2}\frac{\partial}{\partial v}\left[v^2\nu_{\rm E}\left(v\delta f + \frac{T}{m}\frac{\partial \delta f}{\partial v}\right)\right]}_{\text{energy scattering}} + \underbrace{\frac{\nu_{\rm d}}{2}\frac{\partial}{\partial\lambda}(1-\lambda^2)\frac{\partial \delta f}{\partial \lambda}}_{\text{pitch angle scattering}}, \quad \lambda = \frac{v_\parallel}{v}$$

• The effect of ECH is introduced by the quasi-linear heating term $S^{\rm ql}$. In previous study[6], we approximated $S^{\rm ql}$ as a point heating term using the delta function in velocity space.

$$S^{\rm ql} = S_+ - S_-$$

$$S_+ = \frac{S_0}{2\pi v_\perp}\delta(\boldsymbol{x}-\boldsymbol{x}_0)\delta(\boldsymbol{v}-\boldsymbol{v}_{0+})$$

$$S_- = \frac{S_0}{2\pi v_\perp}\delta(\boldsymbol{x}-\boldsymbol{x}_0)\delta(\boldsymbol{v}-\boldsymbol{v}_{0-})$$



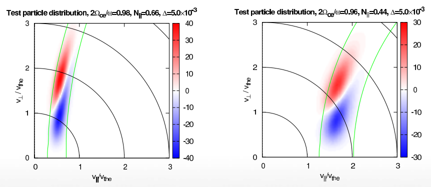
• We modified the ECH heating term to the realistic one.

$$\left(\frac{\partial f}{\partial t}\right)_{\rm ECH} = \frac{1}{v_\perp}\frac{\partial}{\partial v_\perp}\left[v_\perp D_{\rm rf}\left(\frac{v_\perp}{v_{\rm th}}\right)^2\delta\left(\omega - \frac{2\omega_{\rm ce}}{\gamma} - k_\parallel v_\parallel\right)\frac{\partial}{\partial v_\perp}f_{\rm max}\right]$$

$$\sim -\frac{2D_{\rm rf}}{v_\perp}\frac{\partial}{\partial v_\perp}\left[\left(\frac{v_\perp}{v_{\rm th}}\right)^4\frac{1}{\pi^{1/2}\Delta}\exp\left\{-\left(\frac{\gamma(1-k_\parallel v_\parallel/\omega)-2\omega_{\rm ce}/\omega}{\Delta}\right)^2\right\}f_{\rm max}\right]$$

Δ : the broadening factor of ECR condition

• The realistic heating model is given from the EC resonance condition and has the broader distribution in the velocity space (depending on the broadening factor Δ).

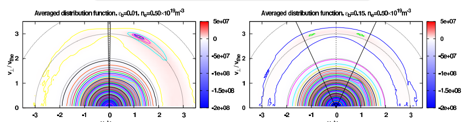


Resonance condition is indicated by the green line.

Simulation result

• We assume a similar plasma parameters with the experiment on Heliotron J, and simulate EC current on three magnetic configurations using the point heating and the realistic heating models.

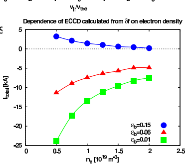
Point heating model



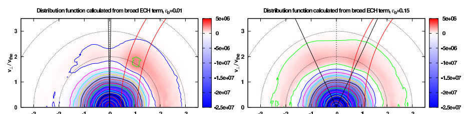
• EC driven current is estimated as follows

$$I_{\rm ECCD} = -e\int v_\parallel \delta f d\boldsymbol{v}$$

• The simulation results agree well with the experimental ones. However, the obtained values of ECCD current is several times larger than that of the experimental ones.

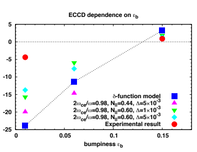


Realistic heating model



• The EC currents calculated from the realistic model denote the same tendency of those of the point model on the magnetic configuration dependence.

• The simulation results of the realistic model show better agreement with the experimental results.



• Taking account of other free parameters such as wave absorption position, the spatial spread of wave absorption or wave absorption rate, we will able to analyze ECCD quantitatively.

Momentum conservation

• The linear Monte Carlo collision operator (e.g. Boozer and Kuo-Petravic model) does not conserve the energy and momentum between test particle and field particle. We improve the GNET code to conserve the momentum.

• The field particle operator $C(f_{\rm Max}, \delta f)$ is introduced in addition to the linear collision operator[7].

$$C^{\rm coll}(\delta f) = C(\delta f, f_{\rm Max}) + C(f_{\rm Max}, \delta f) \qquad C(\delta f, f_{\rm Max}) : \text{test particle operator}$$

• The field particle operator is derived from the Fokker-Planck equation. We can express the collision term, $C(f_{\rm Max}, \delta f)$, using Legendre polynomials as

$$C(f_{\rm Max}(v), \delta f(v,\theta)) = \sum_{n=0}^{\infty} C_n(f_{\rm Max}(v), \delta f^{(n)}(v))P_n(\cos\theta),$$

$$\delta f^{(n)}(v) = \frac{2n+1}{2}\int_0^\pi \delta f(v,\theta)P_n(\cos\theta)\sin\theta d\theta, \quad \delta f(v,\theta) = \sum_{n=0}^{\infty}\delta f^{(n)}(v)P_n(\cos\theta)$$

$$P_0(\mu) = 1, \quad (n+1)P_{n+1}(\mu) = (2n+1)\mu P_n(\mu) - nP_{n-1}(\mu).$$

• Introducing the Rothenbluth potentials, we can describe $C_n(f_{\rm Max}, \delta f^{(n)})$ as

$$\frac{C_n(f_{\rm Max}, \delta f^{(n)})}{f_{\rm Max}(v)} = \Lambda^{e/e}\Big[\delta f^{(n)}(v)$$
$$+2\int_0^{v_e} u^2\delta f^{(n)}(u)\left\{\left(n_+\frac{u^{n+2}}{v_e^{n+1}} - n_-\frac{u^n}{v_e^{n-1}}\right) - \frac{1}{2n+1}\frac{u^n}{v_e^{n+1}}\right\}du$$
$$+2\int_{v_e}^{\infty} u^2\delta f^{(n)}(u)\left\{\left(n_+\frac{v_e^{n+2}}{u^{n+1}} - n_-\frac{v_e^n}{u^{n-1}}\right) - \frac{1}{2n+1}\frac{v_e^n}{u^{n+1}}\right\}du\Big]$$

where $\Lambda^{e/e} = e^4\Lambda_c/\epsilon_0^2 m_e^2$, $v_e = v/v_{the}$ and

$$n_+ = \frac{(n+1)(n+2)}{(2n+1)(2n+3)}, \quad n_- = \frac{(n-1)n}{(2n-1)(2n+1)}.$$

• The field particle term makes the momentum and energy conserved velocity dependence of the momentum and energy loss.

• In this study we just consider the parallel momentum conservation of electrons, so we use only odd number terms of $C_n(f_{\rm Max}, \delta f^{(n)})$.

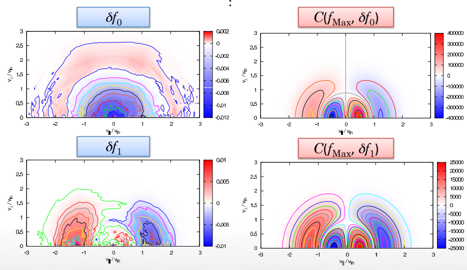
• In order to obtain the field particle term $C(f_{\rm Max}, \delta f)$, we need a solution. Therefore, we iteratively obtain $\delta f = \Sigma_n \delta f_n$ as

$$\frac{\partial \delta f_0}{\partial t} + (v_\parallel + v_D)\cdot\nabla\delta f_0 + \boldsymbol{a}\cdot\nabla\boldsymbol{v}\delta f_0 - C_{lin}(\delta f_0) - L_{\rm particle} = S_{\rm ql}$$

$$\frac{\partial \delta f_1}{\partial t} + (v_\parallel + v_D)\cdot\nabla\delta f_1 + \boldsymbol{a}\cdot\nabla\boldsymbol{v}\delta f_1 - C_{lin}(\delta f_1) - L_{\rm particle} = C(f_{\rm Max}, \delta f_0)$$

$$\frac{\partial \delta f_2}{\partial t} + (v_\parallel + v_D)\cdot\nabla\delta f_2 + \boldsymbol{a}\cdot\nabla\boldsymbol{v}\delta f_2 - C_{lin}(\delta f_2) - L_{\rm particle} = C(f_{\rm Max}, \delta f_1)$$

$$\vdots$$



Conclusion

• In order to study physics of ECCD in helical plasmas, we have simulated the current drive of ECH plasma in Heliotron J by using GNET code.

• The quasi linear ECH term have been modified to the realistic one. Using the realistic and point heating models, we have analyzed ECCD assuming three magnetic configurations similar to those of the experiment.

• The simulation results of the realistic ECH model have been compared with those of the point ECH model, and have shown better agreement with the experimental results.

• It is found that the direction of EC current is reversed in high bumpiness configuration compared with high and low bumpiness configurations. We also found tha the obtained current direction is determined by the balance between Fisch-Boozer effect and Ohkawa effect.

• The momentum and energy conserved collision operator for GNET have been developed and implemented.

Reference

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