Study on ECH driven current at pre-ionization phase of KSTAR experiment

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I. Introduction

During the last year campaign, we had observed the toroidal current when ECH wave was launched for the purpose of pre-ionization. Few hundreds of Ampere was measured without loop voltage. The ECH beam with the frequency of 84 GHz and power of about 400 kW was targeted to the 2^{nd} harmonic resonance layer which is in the field null. ECCD is a conventional method to make non-inductive current for the tokamak operation or for stabilization of NTM but the observation of current at the pre-ionization was seldom reported [1]. The current was induced even in the case of vertical launch of ECH beam to the toroidal magnetic field. In this case there is no preferable toroidal direction for the electrons. The only thing breaking the symmetry is a tiny vertical magnetic field within the field null. The vertical field which gives finite connection length to the electrons and it differs from an electron to an electron. In this point of view, the average life time of electrons flying to clockwise direction is shorter or longer than count clockwise and this could possibly cause the electron current. From this assumption, we can simply deduce the ECH driven electron current for a given density, temperature, and vertical magnetic field. Forest [1] et al. also observed ECH driven current in their tokamak and explained this current by the Pfirsh-Schluter return current, bootstrap current, and toroidal precession of the trapped electrons. Predicted current polarity depending on vertical magnetic field direction, overall amount of current, and even the dependency on vertical magnetic field by Forest's model are almost same and same order with our model except somewhat extreme cases.

II. Simple theory

The electrons born by ECH are tied on the magnetic field and it flies to each of clock and count-clock toroidal directions. In the presence of toroidal field, the electrons inevitably stray out of the field line due to the grad B and curvature drift. In the KSTAR field configuration the drift direction is downward and the electrons leave the heating area in several rounds of the major radius. When the upward vertical field is applied, the magnetic field is slightly inclined. Then the life time of electron flying to count clockwise becomes longer than clockwise electron if B_0 direction is cont clockwise. For simplicity, we use a rough assumption that the electron flying in nearly horizontal direction eventually be the majority because of their longer lifetime compare to others. There are many debatable points but we skip now. We will discuss it next section. Anyhow the electron velocity distributions and the currents for given plasma densities and temperatures are calculated and showed in Fig.1. The plasma column is assumed to have 100 cm^2 as its cross sectional area.

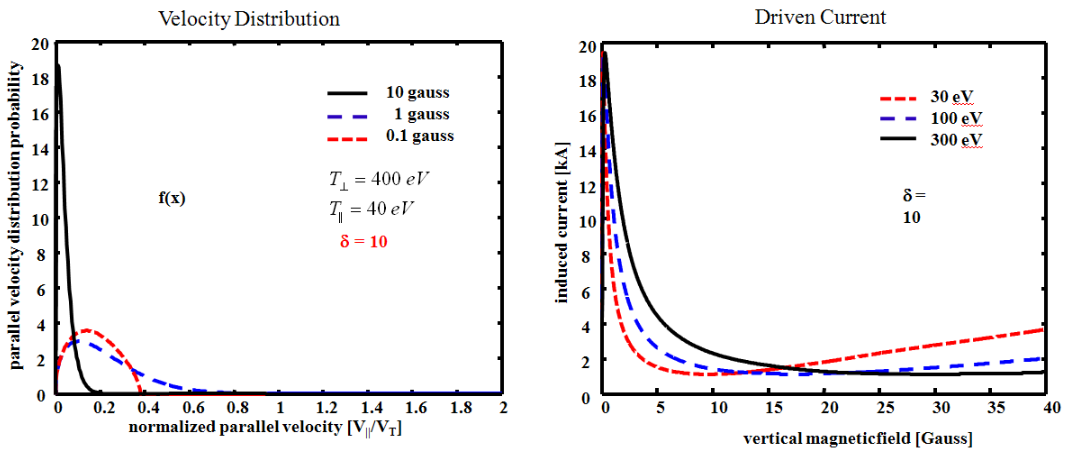

Fig. 1 Predicted the electron velocity distribution and the current for various plasma parameters. The plasma density assumed as 5x1018 cm-3.

The major difference of our model from Pfirsh-Schluter and bootstrap current is the dependency of the current on vertical magnetic field. These two predict that the current is inversely proportional to vertical field. But in our model, as shown in right side of the Fig. 1, the current goes to zero in absence of vertical field and even proportional to vertical field at the strong vertical field even though the overall shape is resemble $1/B_V$.

III. Kinetic considerations

The simple theory gives reasonable amount of the ECH driven current compare to experiments. But the assumption used in deriving the theory is somewhat unnatural. The more realistic version of theory for this phenomenon comes from kinetic consideration of the electron distribution function. The radius of the plasma column is sufficiently small compare to the minor radius and the discharge is intrinsically axisymmetric so that we deal the kinetic equation as 0-D in spatial dimension. In collisionless situation, the lifetime of the electron could be determined by the connection length and its velocity. If we assume that the plasma being produced by the ECH power having maxwellian distribution. Then we can write the 0-D kinetic equation as following

$$\Delta f_{i,j} = -\frac{\Delta t}{\tau_{i,j}} f_{i,j} + \alpha_0 \Delta t\, f^M_{i,j} \qquad (1)$$

Here, $\tau_{i,j}$ is the lifetime of the electron which is on the (i^{th},j^{th}) nodal position of velocity space.

The α_0 is comes from following equation

$$P_{ECH} = \epsilon \frac{dN}{dt} = \epsilon V n_0 \frac{\partial}{\partial t} \int f\, dv^3 = \epsilon V n_0 \frac{\partial}{\partial t} \int \alpha_0 t\, f^M\, dv^3, \qquad \alpha_0 = \frac{P_{ECH}}{n_0 \epsilon V}. \quad (2)$$

Here, V is the plasma volume, ϵ is the average energy of the electron, and P_{ECH} is the ECP power coupled to the plasma. Then we can simply derive the equilibrium electron distribution function from eq. (1) by letting $\Delta f_{i,j}$ to be zero. The equilibrium distribution function is $f_{i,j} = \tau_{i,j}\, \alpha_0 f^M_{i,j}$.

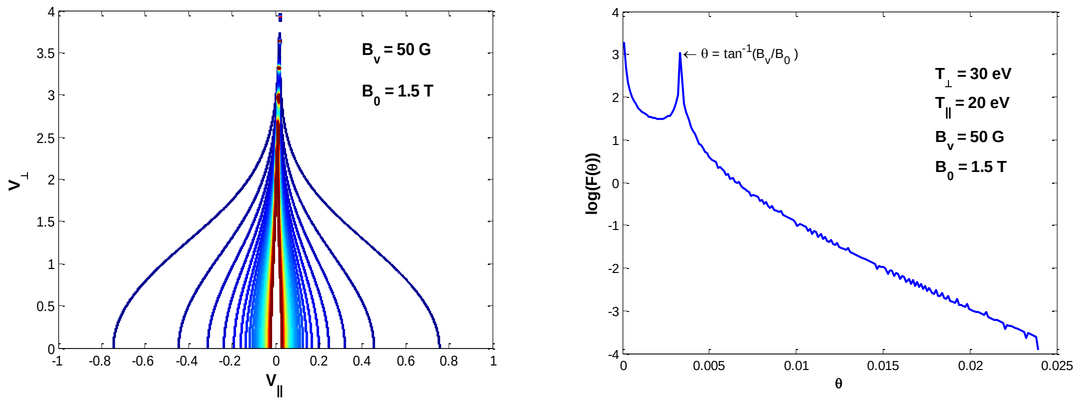

Fig. 2 The electron velocity distribution function when 50 G vertical magnetic field is applied (left) and the electron angular distribution function (right).

Figure 2 shows the deformed equilibrium distribution function and the electron number density function on the angle from magnetic field line. It clearly shows that the number of electron flying to the horizontal direction is increased because of it longevity. Direct integration of the distribution function gives the pure horizontal flux (the current suggested in this paper, $I_{kinetic}$) and pure vertical flux (it causes Pfirsh-Schluter return current).

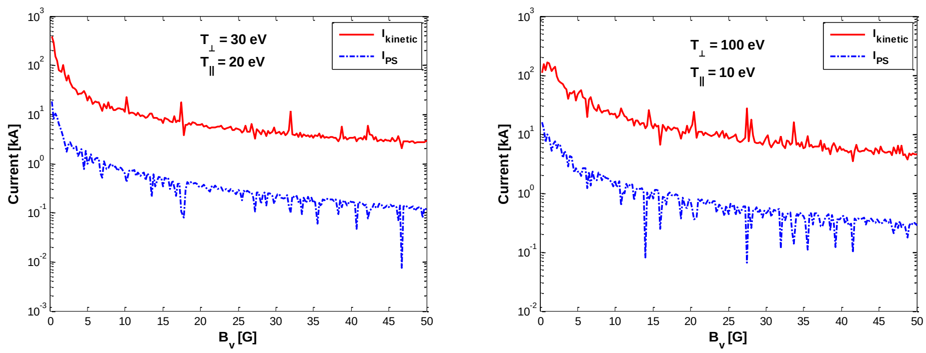

Fig. 3 The current dependences on the vertical magnetic field. The currents are calculated by integrating the distribution function.

Figure 3 shows the current dependences on the vertical magnetic field. The dependencies of the two currents look similar. The parameters used in the kinetic consideration are the same as parameters used in the simple theory. In the parameters ranges we used here, the $I_{kinetic}$

predominates current. But the current amount seems large than the experimentally observed current. If we carefully include the collision effects in the kinetic consideration, the $I_{kinetic}$ will be reduced to more reasonable value.

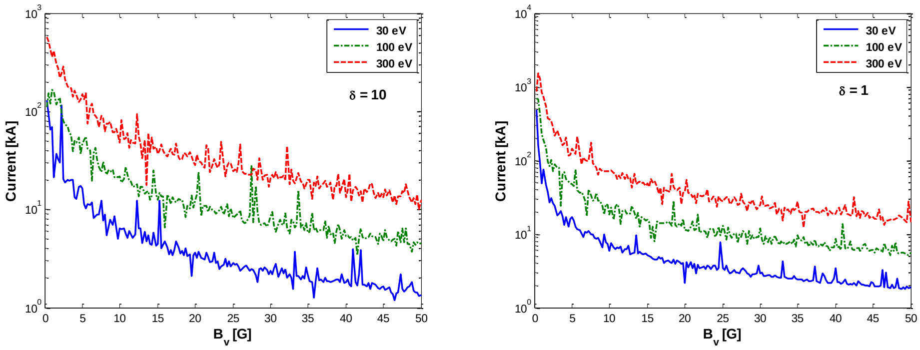

Fig. 4 The current dependences on the vertical magnetic field. Left and right figure are for different $\delta = T_{\perp}/T_{\parallel}$.

Figure 4 shows the tendency of the driven current on the electron temperature and the temperature anisotropy. The current increase as temperature increased. The temperature anisotropy affects not that much the driven current.

IV. Conclusion

We made the simple theory and 0-D kinetic simulation to explain the current driven by ECH wave in pre-ionization discharges. The theory and simulation well agree with the experiment in not only qualitative but also quantitative aspects. The inclusion of collision effects in 0-D kinetic consideration is remained as a future work. It is expected to give more realistic results.

References

[1] C. B. Forest, Y.S. Hwang, M. Ono, and D.S. Darrow, Phys. Rev. Lett. 68, 3559 (1992)