Kinetic study of plasma current generation under microwave power in tokamak plasmas

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Introduction

Non-inductive plasma current start-up is a very important area of research for the spherical tokamak (ST) due to a lack of space for a shielded inboard solenoid. A possible start-up technique, based in the use of radiofrequency (RF) waves for the excitation and absorption of electron Bernstein waves (EBWs), has proven particularly successful [1, 2], with currents up to 73 kA achieved noninductively on MAST with up to 100 kW of input power [3].

An important aspect of the start-up phase is the change of field topology from an open magnetic field line configuration to the formation of closed flux surfaces (CFS). The formation of CFS drastically affects the plasma equilibrium and confinement, and has been observed in a number of RF assisted start-up experiments [1, 2, 3, 4]. The initation of CFS is driven by the generation of a plasma current, for which a number of possible current drive (CD) mechanisms have been proposed and investigated through equilibrium reconstruction and the study of single particle orbits [5, 6]. As such studies are unable to describe the time evolution of observables, they are unable to account for certain experimentally observed effects. We have therefore developed a model for studying RF assisted start-up in order to make interpretations with regards to CD mechanisms, as well as comparisons to experiment, providing further insight into experimentally observed effects during RF start-up.

Kinetic model

Important effects to consider during RF start-up is the plasma-wave interaction and the effect of the open magnetic field lines on particle orbits. In order to ensure the model is tractable, we study the electron distribution function under the assumption that the main physics can be included in zero spatial dimensions (0D) and two momentum dimensions (2V). The time evolution of the distribution function is then studied in the presence of several effects thought to be important in capturing the main physics during the early stages of the plasma discharge,

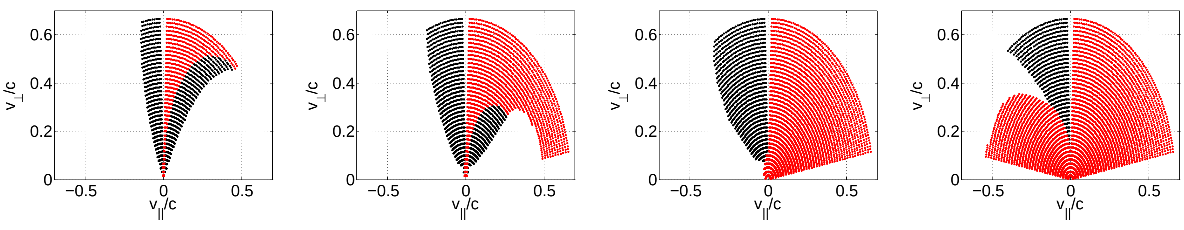
$$\frac{\partial f}{\partial t} = \text{source} - \text{loss} + \text{RF heating} + \text{collisions} + \text{loop voltage} \tag{1}$$

where $f = f(p_\parallel, p_\perp, t)$, $p_\parallel$ is the momentum along the magnetic field, and $p_\perp$ the momentum perpendicular to the magnetic field. In order to account for the 0D nature of the model, appropriate volume averages and approximations are taken [7, 8]. The source term models cold electrons entering the system, the heating term models the plasma-wave interaction, the collision term models electron-electron and electron-ion collisions, and the loop voltage term models plasma induction. These terms are discussed in [7, 8], while only the loss term, modelling the loss of electrons along the open magnetic field lines, is briefly discussed here.

Orbital losses

The initial open magnetic field line configuration during start-up allow electrons to freely stream out of the plasma volume. During this stage, the toroidal magnetic field is typically about two orders of magnitude greater than the poloidal field on the magnetic axis, such that all electrons experience ∇B and curvature drifts in the same direction. By adding a small vertical field, the particle drifts can be cancelled with the parallel motion along this vertical field, resulting in the preferential confinement of electrons moving in a particular direction, and the initiation of a current [9].

The loss term is responsible for modelling the time evolution of the rate at which electrons are lost. The confinement of electrons are dependent on the magnetic field structure, which is determined by the spatial dependence and strength of the vacuum magnetic field and the current density. In order to ensure the model is tractable, the loss term is represented by a 0D approximation, obtained by considering energetic electrons originating from the electron cyclotron layer, where they gain a kick in momentum from interacting with the injected RF beam. By tracing out their orbits, the initial velocities of all electrons completing confined orbits are plotted (see figure 1), and modelled [8].

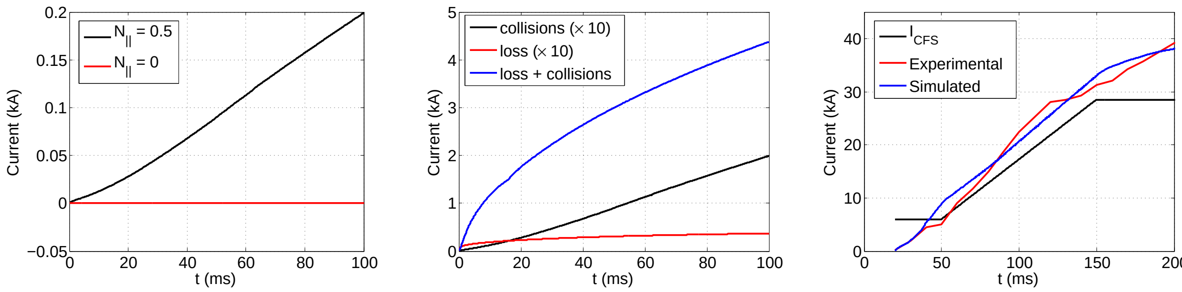


(a) (b) (c) (d)

Figure 1: The initial velocities of confined electrons originating from the electron cyclotron resonance layer to form passing (red) or trapped (black) orbits for $B_V = 10\,\mathrm{mT}$ and increasing plasma current, (a) $I_P = 5\,\mathrm{kA}$, (b) $I_P = 10\,\mathrm{kA}$, (c) $I_P = 15\,\mathrm{kA}$, and (d) $I_P = 20\,\mathrm{kA}$. The first CFS start to form when all forward electrons, with $v_{\|} > 0$, are confined, at $I_P = I_{\mathrm{CFS}} = 15\,\mathrm{kA}$ in this case. Note that electrons with $v_{\|} > 0$ have better confinement than electrons with $v_{\|} < 0$, such that this preferential confinement of electrons can be used to generate a current.

Collisional current drive

The Fisch-Boozer mechanism, based on the preferential heating of electrons moving in one direction to produce an anisotropic plasma resistivity, is an attractive concept for CD using EBW waves. In order to generate a current, the absorbed EBW must have a non-zero value for the parallel refractive index, $N_{\parallel}$. Figure 2(a) shows the generated current for two cases: the preferential heating of electrons with $N_{\parallel} = 0.5$, heats electrons with $p_{\parallel} > 0$, generating a positive current, while $N_{\parallel} = 0$ fails to gain a directionality with respect to the magnetic field, and therefore does not generate a plasma current.



(a) (b) (c)

Figure 2: The time evolution of (a) the plasma current in the absence of electron losses, shows that a favourable value of $N_{\parallel}$ is needed to generate a current. (b) In comparison, a significantly larger current is generated when both losses and collisions are present, indicative of the current drive mechanism through the preferential confinement of electrons. The comparison to experiment (c) shows that the best way to generate larger plasma currents is by increasing the vacuum field strength, which leads to an increase in the value of I_{CFS} and a subsequent increase in I_P while sustaining the asymmetry in electron confinement [8].

Preferential confinement current drive

The addition of a small vertical magnetic field can create a preferential confinement of electrons during start-up, when the magnetic field line configuration is open. This preferential confinement has been used to describe the initiation of CFS, using single particle orbits [2, 5, 6]. Figure 1 shows that the confinement of electrons with $v_{\parallel} > 0$ is much better than electrons with $v_{\parallel} < 0$, such that this preferential confinement can be used to generate a current.

The comparison of the simulated plasma current in three different scenarios is shown in figure 2(b). In the absence of collisions, the plasma current generated by the loss term is even smaller than the current generated by the Fisch-Boozer mechanism. As the EBW heating only increases the perpendicular momentum of electrons, which does not generate a current in itself, the losses of electrons are small. Including collisions allows the parallel momentum of electrons to be increased through pitch-angle scattering, leading to greater losses and a generated current more than 10 times greater than before. The preferential confinement of electrons is therefore responsible for the greater part of the generated current, with collisions only "feeding" the loss term by increasing the parallel momentum of electrons through pitch-angle scattering [8].

Discussion

Experiments on EBW-assisted plasma current start-up concluded that the most efficient method of generating larger plasma currents is by increasing the vacuum field strength [1, 3]. The majority of the plasma current is generated by the preferential confinement of electrons, due to the open magnetic field line configuration. The electron confinement at the value of the plasma current where the first CFS start to form, I_{CFS}, is the most efficient for generating a current, as all electrons with $v_{\|} > 0$ are confined, but not all electrons with $v_{\|} < 0$, as shown in figure 1. An increase in the vacuum field strength will lead to an increase in the value of I_{CFS}, and a subsequent increase in the plasma current I_P, maintaining the asymmetry in the electron confinement [8].

This effect was utilised in experiments conducted on MAST to achieve plasma currents up to 73 kA with up to 100 kW of power [3]. The comparison between the simulated and experimental currents for a 50 kW input is shown in figure 2(c), and shows that the increase in plasma current follows the increase in I_{CFS}, due to the asymmetry in the electron confinement being responsible for the majority of the generated plasma current. The combined effects of collisions, losses, and EBW heating can therefore be used to explain the observed current generated under microwave power in MAST.

Acknowledgements

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