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Modification of the Magneto-Hydro-Dynamic Equilibrium by the Lower-Hybrid Wave Driven Fast Electrons on the TST-2 Spherical Tokamak

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Presence of a large population of fast particles may qualitatively modify the tokamak equilibrium from the one that can be described by the Grad-Shafranov equation^1. Here, we present the first experimental observation of such modification by the lower-hybrid (LH) wave driven fast electrons in a non-inductive plasma. We have performed equilibrium fitting based on the extended magneto-hydro-dynamic (MHD) model that considers a two-component plasma of bulk MHD fluid and kinetic fast electrons. Scrape-off-layer (SOL) current appeared naturally with the extended MHD analysis. The reconstructed poloidal flux surfaces were also more consistent with the density profile measured by the Thomson scattering diagnostic than the one from the conventional equilibrium reconstruction.

Establishment of a fully non-inductive plasma start-up method may lead to a more economical tokamak reactor through removal of the central solenoid. Non-inductive start-up using LH waves has been studied extensively on the TST-2 spherical tokamak ($R_0 = 0.36$ m, $a = 0.23$ m, $B_{t0} < 0.3$ T)^2. The plasma current is mostly carried by LH driven fast electrons that are highly non-thermal and have large orbit excursions from the flux surfaces due to the low plasma current. Substantial fast electron population has been observed with probes in the SOL, which is not trivially described with the Grad-Shafranov equation. The impact of such electrons on the MHD equilibrium was studied by performing a time dependent extended MHD simulation^3. The work showed the possible importance of the fast electron current, but the analysis was mostly theoretical without any experimental validation.

In this study, we have performed equilibrium fitting on the steady state solution of the extended MHD model^{1,3}. The fast electron distribution was parameterized as follows based on the current drive analysis using a ray-tracing and a Fokker-Planck solver^4:

$$f(E, \mu, \psi^*, \sigma) = \mathcal{N} \exp\left(-\frac{\mu B_0}{T_{e0}}\right) \exp\left(-\frac{(\psi^* - \psi_0)^2}{\Delta\psi^2}\right)$$

if $E_{\min} < E < E_{\max}, \sigma = -1$ and $f(E, \mu, \psi^*, \sigma) = 0$ otherwise. E is the electron energy, μ is the magnetic moment, ψ^* is the toroidal angular momentum (per charge) and σ is the parallel velocity sign. The parameters $B_0 = B(R_{\mathrm{LH}}, Z = 0)$, $\psi_0 = \psi(R_{\mathrm{LH}}, Z = 0)$, $\Delta\psi = w_{\mathrm{LH}}(\partial\psi/\partial R)(R_{\mathrm{LH}}, Z = 0)$ were calculated at each fitting iteration. The normalization of the distribution function $\mathcal{N}$ was also calculated each iteration to fix the total fast electron current. The temperature T_{e0} was set to 20 eV from the measured bulk temperature. The minimum and maximum energy of the fast electron plateau was $E_{\min} = 9T_{e0}$ and $E_{\max} = m_e c^2/n_\parallel^2$ ($n_\parallel = 4$) from the current drive analysis^4. The radial position R_{LH} and width w_{LH} and the total fast electron current were optimized to give the best fit to the magnetic and kinetic data. For the kinetic data, the measured electron density profile was fitted to a polynomial of the poloidal flux and the fitting error was added to the magnetics fitting error. Large kinetic fitting error indicates inconsistency between the reconstructed poloidal flux and the measured (bulk) electron density profile under the assumption that it is a flux function.

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Figure 1 shows the results of equilibrium reconstruction performed on a flat top of a typical LH start-up discharge at 16 kA plasma current and 60 kW LH power from the top-launch antenna. The conventional equilibrium reconstruction was performed using third order polynomials as the two free functions. The global parameters were $\beta_p = 0.46$, $l_i = 0.30$, $q_a = 40$. Three additional fast electron profile parameters were optimized for the extended MHD model and the best-fit solution was found where 70 % of the plasma current was carried by the fast electrons. Since we expect that most of the plasma current is carried by the fast electrons, it is promising that this model predicts high fast electron current fraction despite its simplicity. The electron density profile fitting (Fig. 1 (a)) improved by 32 % with the extended MHD model compared to the conventional equilibrium reconstruction with no fast electrons. The improvement was mostly from better fitting of points around $R = 0.5$ m. The fast electron current varied as $\sim 1/R$, which is similar to the poloidal current function of the Grad-Shafranov equation. However, expansion of the current profile into the SOL (Fig. 1 (d)) allowed for the bulk pressure function to be reduced and the current density was more concentrated on the high-field side with extended MHD (Fig. 1 (b)). The generated poloidal flux profile was more peaked (Fig. 1 (c)), which matched better the measured electron density profile (Fig. 1 (a)).

The SOL current appeared naturally in the extended MHD model. By coupling this model with a finite-orbit Fokker-Planck solver, we can quantitatively study the wave-particle interactions in the SOL, which are known to degrade core current drive efficiency. The model can also describe plasma without any closed flux surfaces: the feature essential to simulate closed flux surface formation. The model is applicable whenever collisionless fast electrons play the dominant role. This includes not only LH start-up, but also electron cyclotron wave driven and assisted start-up, which may be essential for future reactors.

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