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A simulation environment to simulate lower-hybrid-wave-driven plasmas efficiently

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ABSTRACT

In this study a hybrid simulation environment to investigate the lower-hybrid-wave-driven tokamak plasmas is presented, and its application to the spherical tokamak TST-2 is described. These plasma are formed and driven by radio-frequency waves without the use of the central solenoid, and are characterized by low density and low magnetic field. A hybrid simulation environment which is divided into two groups, one using magneto-hydrodynamic (MHD) as well as particle-in-cell (PIC) approaches, and the second group using ray-tracing and Fokker–Planck solvers, is applied to describe the behavior of energetic electrons, bulk plasma, wave propagation, and the wave-particle interaction. Both groups of solvers can be coupled via the energetic-particle velocity distribution function and the equilibrium conditions of magnetic field, pressure, and density profiles to obtain a self-consistent solution. First results show the impact of a self-consistent equilibrium on ray trajectories and current density profiles. Therefore, new insights in lower-hybrid-wave-driven plasmas of TST-2 can be obtained using the proposed hybrid simulation environment.

1. Introduction

Spherical tokamaks (ST) possess the significant advantage of high β plasma capability at low magnetic field. However, until today it is not feasible to realize a compact ST reactor at low aspect ratios ($A \leq 1.5$) without eliminating the central solenoid [1,2]. During the steady-state burning phase, the plasma current could be maintained mainly by the self-driven current possibly assisted by a neutral beam current drive. To reach a sufficiently high plasma current level for burning plasma in an ST fusion reactor, there is until today no established method of effective current ramp-up without the use of the central solenoid. Note that in conventional tokamaks with aspect ratios $A > 3$, the plasma current was successfully ramped up by the lower-hybrid (LH) waves without using the central solenoid [3,4]. Conventional ratio tokamaks are favorable for LH current drive since the plasma dielectric constant is lower because of the higher magnetic fields compared to ST devices [5]. In TST-2, an ST device with major radius $R_0 = 0.36$ m, minor radius a=0.23 m, aspect ratio $A = R_0/a \geq 1.6$, toroidal magnetic field $B_t \leq 0.3$ T, and plasma current $I_p \leq 0.14$ MA [6], non-inductive plasma current start-up using LH waves has been investigated thoroughly [7–11]. A recently installed capacitively coupled combline (CCC) antenna [11] has a coupling efficiency of nearly 100% and can be applied at high power. Recently, plasma current ramp-up to 25 kA has been achieved injecting 74 kW of net RF power at 200 MHz. Furthermore, recent measurements showed that the bulk temperature profile is hollow, which also implies that the toroidal current density profile might also be hollow. Furthermore, in the TST-2 experiments, a small fraction of electrons at high energy are thought to carry almost the entire plasma current [12].

In the past, several numerical methods with different focus on the physics to be described have been applied to understand the TST-2 LH-driven plasmas. Initially, equilibrium reconstruction of such a plasma has been carried out using the Grad–Shafranov approach [13,14]. Then, a full two-fluid equilibrium model [15,16] was applied to describe a solenoid-free RF sustained ST plasma [17]. However, a certain part of the electrons being accelerated by the RF wave has higher temperatures compared to bulk electrons, i.e., there are low-density high-temperature electrons and high-density low-temperature electrons. To that end, Ishida et al. [18] developed for the simulation of collisionless ST plasmas sustained by strong RF electron heating a 3-fluid approach including MHD ordering and neglecting the gyroviscous cancellation. The plasma considered here consists of high-density

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low-temperature electrons, low-density high-temperature electrons, and high-density low-temperature ions [19]. This 3-fluid model assumed, however, that all three components have isotropic temperatures, the ion fluid is singly ionized, and that equilibrium is axisymmetric. Especially the first assumption may not describe the plasma conditions in TST-2, since studies have shown that the energetic electrons exhibit strongly anisotropic "temperatures", i.e., parallel forward temperatures are higher than perpendicular and parallel backward components along with a distribution function that is significantly different from being Maxwellian. Furthermore, the 3-fluid code uses a system of nine profile functions depending strongly on the initial choice of the shape of profiles made by the user.

Other numerical studies focused on the LH current drive mechanisms rather than the effects of resulting current profile on the ST plasma equilibrium. Previous LH current drive modeling has been largely qualitative [7,10], because of the lack of detailed density and temperature profile information. Furthermore, some plasma parameters were tuned artificially to obtain converged simulations. A more sophisticated simulation including density and temperature profiles measured by Thomson scattering diagnostic [12] was presented recently [20], where a ray-tracing solver GENRAY [21] and a bounced-averaged Fokker–Planck solver CQL3D [22] were coupled using EFIT [23] equilibrium field for peaked distributions. It was observed that the current carrying electrons do not penetrate to the core region for a fixed magnetic field geometry such that the force balance of the plasma was not solved self-consistently. However, it was shown that for LH-driven, fully non-inductive discharges in TST-2, the correlation between the plasma current and density could be explained by using coupled GENRAY and CQL3D simulations. Still, finite orbit width, radial diffusion through collisions, and RF quasilinear diffusion were not included in the CQL3D simulation such that the quantitative analysis of RF plasma remains challenging [20].

The goal of this study is to introduce a hybrid simulation environment which is capable of simulating the conditions of an LH-driven TST-2 covering MHD fluid interacting with energetic particles, distribution function evolution via Fokker–Planck equation by RF quasilinear diffusion and collisional relaxation, and wave propagation and absorption via ray tracing. Therefore, it can handle arbitrary distribution functions, and hence, energetic electron density, pressure, and current density profiles self consistently. Since the contribution of the bulk plasma to the total pressure is about two orders of magnitude lower compared to the energetic particle contribution [12], the focus of this study is set to the significant modifications of the magnetic field configuration due to the presence of the energetic electrons.

The paper is organized as follows. First, the numerical methods are introduced in detail and the simulation procedure within the simulation environment is described. Then, the computational setup using a TST-2 LH-driven plasma configuration is given and finally, the results of the simulation environment are verified and analyzed using convergence studies and a fully coupled simulation of a typical TST-2 LH-driven plasma.

2. Numerical Methods

In the past, on the one hand the coupled GENRAY/CQL3D simulation has been proven useful [11,20] to evaluate LH-wave-driven plasmas in spherical Tokamaks. On the other hand, the MHD-kinetic particle code MEGA [24–27] has been successfully applied to investigate the interaction between energetic particles and the bulk plasma. For those reasons, these codes are combined and introduced in the following paragraphs whereas the focus is on MEGA since the main part of the computation applies this simulation.

2.1. Solvers

MEGA: To simulate the evolution of the energetic electrons interacting with a low-temperature bulk plasma, MEGA, a hybrid simulation code for MHD and energetic particles, is applied. In the MEGA code, the bulk plasma is described by the non-linear MHD equations and the energetic ions are simulated with the full-f method instead of the δf particle method [28] since the simulation procedure detailed in Section 2.2 targets a significant spatio-temporal modification of the self-consistent equilibrium solution. The MHD equations with the energetic-electron effects are given by

$$\frac{\partial n_i}{\partial t} = -\nabla \cdot (n_i \vec{v}) + \nu_n \Delta \left(n_i - n_{eq}\right), \tag{1}$$

$$\begin{aligned} m_i n_i \frac{\partial}{\partial t}\vec{v} = &- m_i n_i \vec{\omega} \times \vec{v} - m_i n_i \nabla \left(\frac{v^2}{2}\right) - \nabla p + \left(\vec{j} - \vec{j}_h\right) \times \vec{B} \\ &- \nabla \times (\nu m_i n_i \vec{\omega}) + \frac{4}{3}\nabla (\nu m_i n_i \nabla \cdot \vec{v}), \end{aligned} \tag{2}$$

$$\begin{aligned} \frac{\partial p}{\partial t} = &- \nabla \cdot (m_i n_i \vec{v}) - (\gamma - 1) p \nabla \cdot \vec{v} + (\gamma - 1) \\ &\times \left[\nu m_i n_i \vec{\omega}^2 + \frac{4}{3}\nu m_i n_i (\nabla \cdot \vec{v})^2 + \eta \vec{j} \cdot \left(\vec{j} - \vec{j}_{eq}\right)\right] \\ &+ \nu_n \Delta \left(p - p_{eq}\right), \end{aligned} \tag{3}$$

$$\vec{E} = -\vec{v} \times \vec{B} + \eta \left(\vec{j} - \vec{j}_{eq}\right), \tag{4}$$

$$\vec{j} = \frac{1}{\mu_0} \nabla \times \vec{B}, \tag{5}$$

$$\frac{\partial B}{\partial t} = -\nabla \times \vec{E}, \tag{6}$$

$$\vec{\omega} = \nabla \times \vec{v}, \tag{7}$$

where n_i is the bulk-ion number density, m_i is the ion mass, μ_0 is the vacuum magnetic permeability, γ is the adiabatic constant, η is the resistivity, ν and ν_n are artificial viscosity and diffusion coefficients are chosen to maintain numerical stability. All the other quantities are conventional, whereas the subscript $_{eq}$ represents the equilibrium variables at the beginning of the MEGA simulation. Regarding the electromagnetic field, the standard MHD formulation is applied, and using j_h in the MHD momentum equation the energetic electron contribution is included in the final coupled formulation. Note that the model accuracy does not depend on the condition that the energetic-particle density has to be significantly lower than the bulk plasma density, since electrons are used. However, in the present study the energetic electron density never exceeds 10% of the bulk-ion density. Using a fourth-order difference scheme the MHD equations are solved in space and time.

The energetic particles are described by the drift-kinetic equations [29], where the guiding-center velocity u of the electrons is given by

$$\vec{u} = \vec{v}_{\parallel}^* + \vec{v}_E + \vec{v}_B, \tag{8}$$

$$\vec{v}_{\parallel}^* = \frac{v_{\parallel}}{B^*}\left(\vec{B} + \vartheta_{\parallel} B \nabla \times \vec{b}\right), \tag{9}$$

$$\vec{v}_B = \frac{1}{B^*}\left(-\mu \nabla B \times \vec{b}\right), \tag{10}$$

$$\vec{v}_E = \frac{1}{B}^* \vec{E} \times \vec{b}, \tag{11}$$

$$\vartheta_{\parallel} = \frac{m_h v_{\parallel}}{e_h B}, \tag{12}$$

$$\vec{b} = \vec{B}/B, \tag{13}$$

$$B^* = B\left(1 + \vartheta_{\parallel} \vec{b} \cdot \nabla \times \vec{b}\right), \tag{14}$$