An implicit full f particle method for studies of Alfvén waves and energetic particle physics

Zhixin Lu[1], Guo Meng[1], Matthias Hoelzl[1], and Philipp Lauber[1]
[1] Max Planck Institute for Plasma Physics
e-mail (speaker): zhixin.lu@ipp.mpg.de

The full f particle simulations have attracted significant efforts motivated by the studies of global effects and edge physics [1]. In our previous work, a mixed particle-in-cell (PIC)-particle-in-Fourier (PIF) approach has been implemented in TRIMEG (TRIangular MEsh based Gyrokinetic) code using an explicit scheme and unstructured meshes [2]. Implicit PIC with specific discretization scheme in slab geometry has been reported featured with good properties such as energy and momentum conservation and the capability of allowing large time steps [3].

In this work, an implicit scheme for electromagnetic particle-in-cell/Fourier simulations is developed using the $v_\|$ formula and applied to studies of Alfvén waves in one dimension and in tokamak plasmas on structured meshes [4]. While the "particle enslavement" scheme has been introduced for reducing the degree of freedom of particles in the field-particle system [3], in this work, we focus on the theoretical analyses of the convergence of the system. An analytical treatment is introduced to achieve efficient convergence of the iterative solution of the implicit field-particle system. The essence of this scheme is to represent the particle moments such as the density and the parallel current as functions of field variables. Then the correction matrix of the implicit field-particle system can be obtained analytically. As a result, this treatment is termed with "moment enslavement".

Its application to the one-dimensional uniform plasma demonstrates the applicability in a broad range of β/m_e values. The simulation results and the theoretical results agree well in our studied regime where $\beta_e m_i/m_e \in [1/16, 32]$, $k_\perp \rho_{ti} = 0.2$, where β_e is the electron beta, $k_\perp$ is the perpendicular (to $\boldsymbol{B}$) wave vector, ρ_{ti} is the Larmor radius of thermal ions, m_i and m_e are ion and electron masses.

The toroidicity induced Alfvén eigenmode (TAE) is simulated using the widely studied case defined by the ITPA Energetic particle (EP) Topical Group. The real frequency and the growth (or damping) rate of the TAE with (or without) EPs agree with previous results reasonably well. For $m_i/m_e = 200{,}1836$, the real frequency ω_r and the damping rate γ are $(0.9615, -0.011999)\omega_{TA}$, $(0.98142, -0.004907)\omega_{TA}$, respectively, from TRIMEG simulations, where $\omega_{TA} = v_A/(2qR_0)$. The ratio between the damping rate and the real frequency from TRIMEG, $\gamma/\omega - 1.248\%$ for $m_i/m_e = 200$, and $\gamma/\omega = -0.5000\%$ for $m_i/m_e = 1836$, agree well with that from the kinetic eigenvalue code LIGKA ($\gamma/\omega = -1.293\%$, $\gamma/\omega = -0.5008\%$).

The full f electromagnetic particle scheme established in this work provides a natural choice for EP transport studies where large profile variation and arbitrary distribution need to be captured in kinetic simulations. By combining the recent developments from [3, 4], with the applications to mode structure symmetry breaking studies [5], the ongoing work focuses on the simulations of kinetic ballooning mode simulations and EP driven Alfvén modes in realistic tokamak geometry, with the capability of including the plasma separatrix. The full f and delta f simulations are compared, demonstrating their features in performance and the capabilities of the full f scheme in treating specific problems.

This work is supported by the EUROfusion Enabling Research Projects WP19-ER/ENEA-05 and WP19-ER /MPG-03. This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the EURATOM research and training programme 2014-2018 and 2019-2020 under grant agreement No. 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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