Fully kinetic Particle-in-Cell simulations of the tearing mode instability in tokamaks

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Abstract

The tearing mode instability could destroy the plasma confinement in fusion tokamaks and its mechanism is still not fully understood. Here we present the fully kinetic Particle-in-Cell (PIC) simulations of the tearing mode in tokamaks using an energy-conserving and semi-implicit PIC code ECsim. The formation and evolution of magnetic islands are presented and the computation cost proves to be large. More results will be given in the future.

Introduction

Instability in fusion tokamaks is dangerous because it could change the magnetic flux surface structure, destroy the confinement and even cause disruptions. The tearing mode instability is one example. There have been lots of studies on tearing mode during the past several decades but its mechanism is still not fully understood. The simulation of plasmas in tokamaks is challenging due to its multiscale feature [1].

The tearing mode instability was first thoroughly studied by Furth [2] theoretically. Much research has also been devoted to magnetohydrodynamics (MHD) and gyrokinetic simulations recently. Zhang W et al. upgraded their MHD code and studied Hall effects on the evolution of tearing modes and found that the linear growth rate is connected with the ion skin depth [5]. They also studied the effect of helical driven current on nonlinear resistive tearing mode evolution and saturation [6]. Zhang R et al. [3] developed a new field solver for the gyrokinetic particle-in-cell code GEM to achieve low-n (n=1,2) MHD tearing mode simulations in toroidal geometry. They systematically investigated the effects of toroidicity and kinetic ions on the resistive tearing modes and compared their results with analytic theory. They also studied the

effect of kinetic ions on the Double Tearing Mode evolution[4].

However, MHD simulations may not be able to reflect the actual nature of tearing mode as the collisions in core region are rare in tokamaks. On the other hand, the tearing mode is related to magnetic reconnection and the gyro-kinetic approximation may not be accurate enough to describe the kinetic evolution in current sheets, which is significant for the dynamics during the magnetic reconnection process. As a result, it is plausible to investigate this problem using fully kinetic methods. The purpose of this study is to investigate the evolution of the tearing mode using a semi-implicit fully kinetic Particle-in-Cell (PIC) code.

The remaining part of the paper proceeds as follows: The methods used and the simulation setup are presented in section 2. The simulation results are described in section 3. Finally the conclusions and discussion are given in section 4.

Simulation methods and setup

ECsim is a new energy-conserving semi-implicit particle-in-cell (PIC) code developde by Lapenta el al [7]. A mass matrix is implemented in ECsim and the detailed algorithm could be found in [7–9]. The equilibrium used for tearing mode simulation is got from NOVA [10, 11] (the same as [5]). The simulation domain is a 3-dimensional tokamak geometry (Fig. 1) whose major radius is 4 and minor radius is 1. The mass ratio is $m_i/m_e = 256$. The length in ECsim is normalized with ion skin depth di and the normalized dimension of the box is $Lx \times Ly \times Lz = 190 \times 44 \times 190$. The time is normalized with the inverse of ion plasma frequency and the time step dt used is 1. The grids number is $256 \times 100 \times 256$ and 512 particles are allocated in each cell. At the moment we only resolve the ion scales.

The lambdadamping boundary method is used in the simulation. When $\lambda = 0$ the Maxwell equations would be solved while there would be a coefficient λ to damp the fields if the λ is nonzero. The particles would be removed in the cells whose λ is nonzero. We also set a smoothing at the interface between $\lambda = 0$ and λ is nonzero.

Results

2-Dimensional simulation

In order to check the feasibility of the simulation, we first conducted 2-dimensional simulation with the initial equilibrium using higher resolution.

3-Dimensional simulation

The 3-dimensional simulation is conducted using the parameters in section 2.

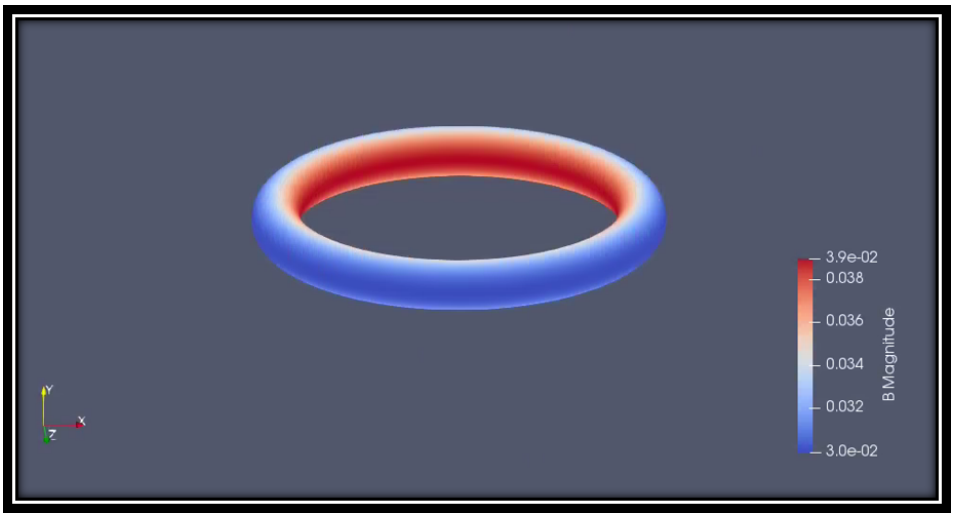

Figure 1: Tokamak geometry

We run nearly 17,000 cycles in total. The poincare plot of cycle=2300 is shown. We could observe some islands in this plot and we think this is a process of the equilibrium adjustment. The initial equilibrium we got from NOVA is a MHD equilibrium and we converted it into a kinetic equilibrium. The current density was set to be electron current and the initial ion current density is set to be 0. This setup leads to the relaxation of the equilibrium and we can get a more reasonable kinetic equilibrium when we continue to run the simulation, as shown in ??.

When we run a longer cycle, we got the formation process of magnetic islands as shown in ??. We can observe a few magnetic islands at the $q = 2$ (q is the safety factor) surface. However, if we want to get the final tearing mode, we may need to run as long as [5] and this lead to a very large simulation. In order to decrease the computation cost, we tried different ways including using a smaller mass ratio and changing the c (speed of light) in ECsim. This is still in process.

Conclusion and discussion

The fully kinetic Particle-in-Cell simulation of the tearing mode instability in tokamaks is presented in this article. It is shown the fully kinetic simulations could resolve the electron scale while the computation cost is very large. Now we are doing a benchmark to verify the reliability of our simulations and next we plan to find ways to decrease the computation cost and use a more advanced HPC platform to conduct this simulation.

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