GLOBAL PIC SIMULATION OF RF WAVES IN TOROIDAL GEOMETRY

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Abstract

We report on nonlinear PIC simulations of wave-wave and wave particle phenomena relevant for RF heating and current drive schemes in tokamaks. For this we have developed a new nonlinear kinetic simulation model based on the global toroidal code GTC. In this model, the ions are considered as fully kinetic particles obeying the Vlasov equation and the electrons are treated as guiding centers that are evolved by the drift kinetic equation. We have benchmarked this numerical model to verify the linear physics of normal modes, conversion of slow and fast waves and its propagation in the core region of the tokamak using Boozer coordinates. In the nonlinear simulation of ion Bernstein wave (IBW) in a tokamak, parametric decay instability is observed where a large amplitude pump wave decays into an IBW sideband and an ion cyclotron quasi-mode (ICQM). The ICQM induces an ion perpendicular heating, with a heating rate proportional to the pump wave intensity. Finally, in the electromagnetic lower hybrid wave simulation, nonlinear wave trapping of electrons is verified and plasma current is nonlinearly driven in the core region. However, in many experiments, parametric decay instability is usually observed in the scrape-off layer (SOL). We have upgraded GTC to enable global toroidal simulations that couple the core and SOL across the separatrix by using cylindrical coordinates with field-aligned particle-grid interpolations. Using this new tokamak geometry model, we have implemented the fully kinetic particle pusher to capture the high frequency (ion cyclotron frequency and beyond), and the particle dynamics of guiding center associated with the low frequency waves. To verify the new simulation model, we have carried out simulations to study ion orbit loss at the edge of the tokamak plasma with single null magnetic separatrix for DIII-D tokamak. The ion loss conditions are examined as a function of pitch angle for cases both with and without an electric field.

INTRODUCTION

The importance of radio frequency (RF) waves for steady state operation of fusion experiments has been recognized from the early days of tokamak research, ever since it was predicted that the power dissipated by waves having high phase velocities could be much smaller than previously thought of. Now there are many methods of current drive considered in present-day tokamaks and for the future burning plasma experiment ITER [https://www.iter.org]. Besides its role to provide a steady state operation, RF can also provide for plasma stabilization.

Although encouraging results have been obtained for successful use of the Lower Hybrid (LH) wave in tokamak, recent studies have pointed out the importance of the edge plasma characteristics on the core absorption of the LH wave that could change the standard picture of first principle LH wave modelling that has been carried out up to now. The non-thermal bremsstrahlung in the hard x-ray range of photon energy (HRX) used as a measure of the current drive efficiency is found to fall off rapidly with the density, a scaling law that is ascribed to parasitic absorption of the LH wave by collisional damping in the dense surrounding scrape-off layer (SOL) outside the separatrix [1,2]. Besides, in plasma conditions for which the LH wave absorption is weak, ray tracing (C3PO/LUKE) simulation shows that introducing fast fluctuations of the power spectrum at the separatrix leads to an improved agreement between modelling and observations in the Tore Supra tokamak, in particular concerning the HXR profile.

Quantitative simulations of LH driven discharges have become a standard in modelling and are essential for an accurate physics assessment. When the spectral gap is moderate, LH simulations based on standard toroidal refraction are in quantitative agreement with the non-thermal bremsstrahlung emission (HXR) profiles and the plasma current. However, the LH current may be sensitive to the antenna directivity while HXR profiles are more robust and relevant to power absorption in general. Also, simulations of LH current drive experiments when the spectral gap is large have always been a difficult exercise, because of the possible onset of chaotic behaviour before the full absorption of the LH wave. This makes predictions sensitive to small variations of any parameters of the simulations. In this regime, the predicted HXR profiles usually disagree with experimental measurements. For large spectral gap conditions, introduction of fast fluctuations of the power spectrum (tail LH model) lead to an improved quantitative agreement between observations and simulations using C3PO/LUKE code [3]. This model leads also to an improved quantitative agreement with experimental observations for full current drive diverted discharges in the EAST and Alcator C-Mod tokamaks. Fluctuations of the power spectrum at the separatrix lead to a more progressive power absorption of the LH wave as it propagates in the plasma and a well-developed tail of non-thermal electrons by Landau damping. The power absorption is therefore more central, especially for diverted magnetic configurations which are particularly favourable for a strong off-axis refraction.

In many RF experiments, parametric decay instability (PDI) is usually observed in the scrape- off layer (SOL). Also, standard modelling based on toroidal refraction only becomes more challenging when the spectral gap at the plasma edge is large, except if other physical mechanisms may dominate to bridge it, like parametric instabilities describing the nonlinear mode coupling, as suggested for JET LH discharges [4].

1. SIMULATION OF RF WAVES IN THE CORE REGION

The gyrokinetic toroidal code (GTC) has been involved in the study of plasma transport in the core region of the tokamak for the last two decades. The GTC [5] is a well-benchmarked full torus particle-in-cell (PIC) code for first-principles simulations of multiple kinetic-MHD processes in fusion plasmas. A single GTC electromagnetic version is currently capable of simulating neoclassical transport, microturbulence, mesoscale Alfven eigenmodes excited by energetic particles, and macroscopic MHD modes (kink and resistive tearing modes). The ions can be either fully kinetic (for RF heating and current drive) [6,7,8,9] or gyrokinetic (for kinetic-MHD processes).

In addition, with the verification of RF waves in toroidal geometry, we have carried out the propagation of LH waves in the core region. The central value of the poloidal spectrum of the LH wave-packet increases and the spectrum broadens when the wave penetrates towards the plasma center, which is due to the poloidal asymmetry of the magnetic field and the wave diffractions. The poloidal spectrum upshift and broadening effects for explaining 'spectral gap' problem are observed and verified in global particle simulation for the first time [10].

Also, we have applied the new tool for studying the nonlinear RF physics in fusion plasmas. In our nonlinear simulations, PDI is observed where a large amplitude pump wave decays into an IBW sideband and an ion cyclotron quasimode (ICQM). The ICQM induces an ion perpendicular heating, with a heating rate proportional to the pump wave intensity [8] . These results provide important insights for experimental observations.

2. SCRAPE-OFF-LAYER (SOL) SIMULATION CAPABILITY IN GTC

Present version of GTC normally uses conventional magnetic flux (Boozer) coordinates, in which the equations of motion encounter a mathematical singularity of metric on the magnetic separatrix surface. A particular feature in the upgraded GTC will be the use of a cylindrical coordinate system for the advancement of the particle dynamics, which allows particle motion in arbitrary shaped flux surfaces including the magnetic separatrix and the magnetic X-point. As a first step in developing this self-consistent global geometry particle simulation model, we construct the field-aligned computational mesh in cylindrical coordinates to take advantage of the long parallel wavelength by using a small number of grid points in the direction of the magnetic field. The mesh provides a high resolution in any given poloidal plane using the more fundamental cylindrical coordinates rather than the flux coordinates [8]. The gain in computational efficiency by using suitable coordinates and a proper computational mesh will help to optimize turbulence simulations in large devices like ITER. The trajectories of the fully-kinetic (FK, Blue and green) and guiding center (GC, cyan and yellow) trapped particle orbits on the R-Z plane in the core and cross-separatrix regions are shown Fig. 1 [11].

Both integrators correctly capture the trapped particle orbits and agree well with each other. The conservation properties of our integrators are confirmed with two exact constants of motion, viz., kinetic energy and toroidal angular momentum.

To verify simulation model further, we have carried out simulations to study ion orbit loss at the edge of the tokamak plasma with single null magnetic separatrix for DIII-D tokamak. Also, we have demonstrated the shift of velocity space boundaries separating trapped and passing ion orbits in the presence of a radial electric field (cf. Fig.2).

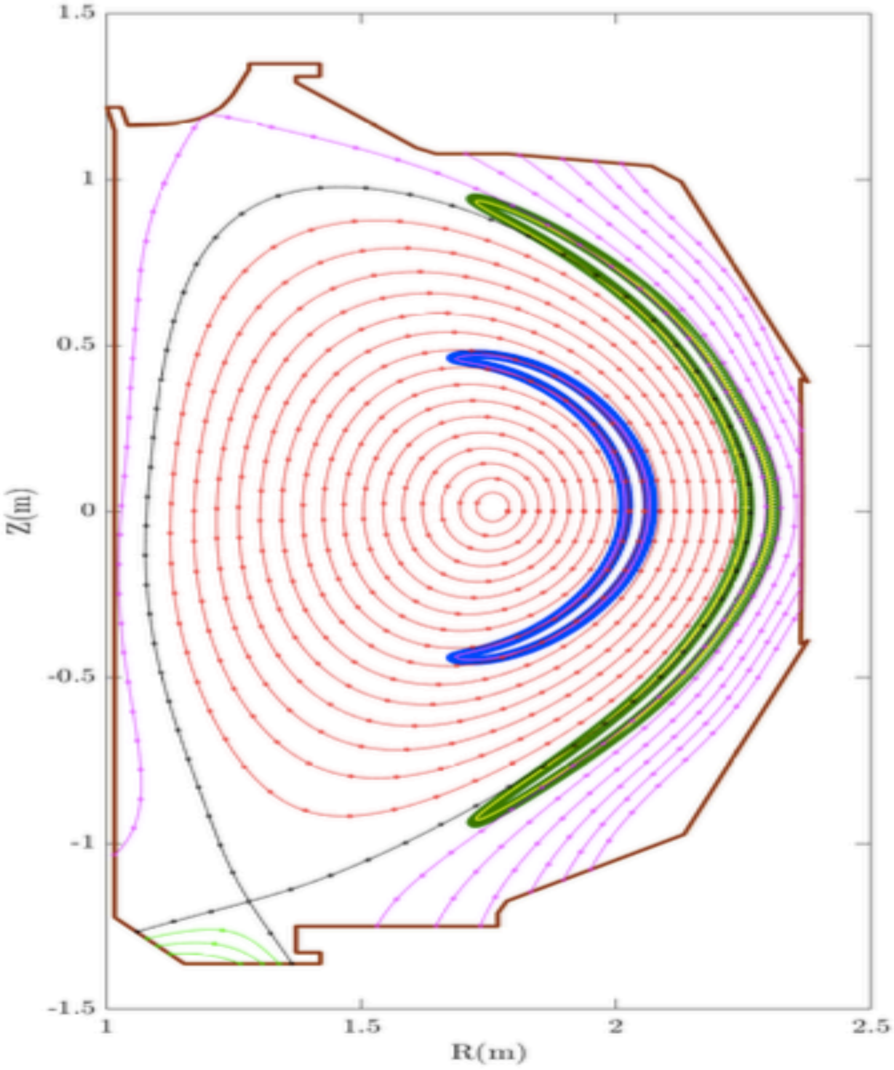

Fig. 1 GTC computational grids on a poloidal plane coupling core and SOL. Field aligned mesh at the core, separatrix, SOL, and private regions are represented by red, black, magenta, and green, respectively. Fully kinetic (blue and green) and guiding center (magneta and yellow) calculations of trapped particle orbits in the core (51.66keV) and cross separatrix (59.42keV) for DIII-D shot #158103 at 3050 ms. Limiter points are represented by dark brown line.

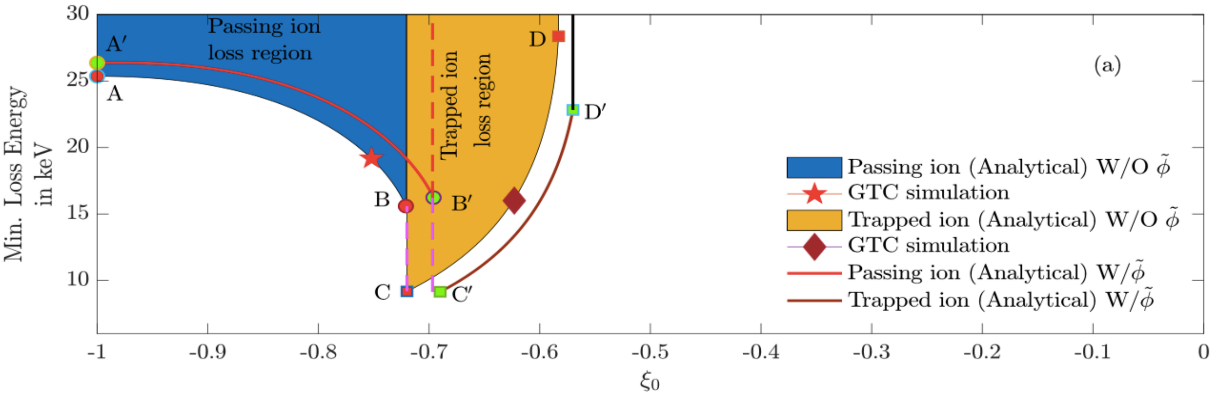

Fig.2 Ion orbit loss region for DIII-D in the initial velocity space, i.e., the minimum energy for which the orbits of ions launched from outer mid plane will be lost. The electric field shows the shift of velocity space boundaries of trapped and passing ion.

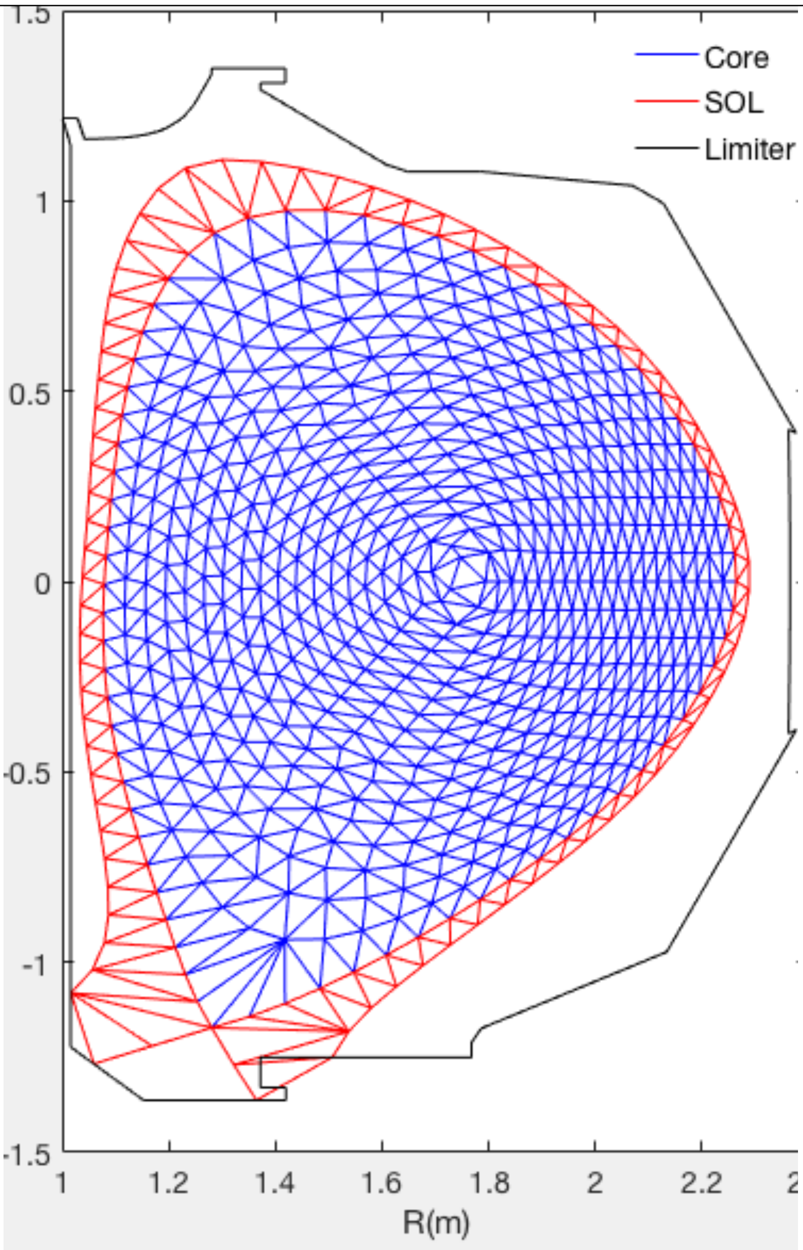

Fig.3 Triangular mesh with diverted magnetic field for DIII-D.

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