Effects of Transport and Non-thermal Particles on Kinetic H-mode Pedestal Evolution with ELMs

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Abstract. A coupled kinetic-MHD edge plasma model is used in simulations to investigate the dynamics of Edge Localized Modes (ELMs). In addition, the effects of transport and non-thermal particles are used in simulations of kinetic H-mode pedestal evolution in order to optimize tokamak performance. Results of hybrid modeling of an ELM cycle in DIII-D geometry are presented. The kinetic XGC0 code (`http://w3.physics.lehigh.edu/~xgc`) is used to model the dynamic evolution of the plasma edge region, including the formation of an H-mode pedestal. The ideal MHD stability code ELITE is used to check the peeling-ballooning triggering conditions for an ELM crash, and the extended MHD NIMROD code (`http://nimrodteam.org/`) is used to follow the ELM crash dynamics. In the simulations of DIII-D discharges, it has been shown that two-fluid and FLR effects can significantly change the spectrum of unstable ballooning modes and the dynamics of an ELM crash. As a result of diamagnetic effects, the ELM filaments become strongly sheared in the poloidal direction in the coupled XGC0-NIMROD simulations of an ELM cycle for the DIII-D discharges studied. New developments in the XGC0 code are described in this paper, including the implementation of the beam geometry package from the NTCC NUBEAM module and an interface to anomalous transport models from the Framework for Modernization and Componentization of Fusion Modules (FMCFM). The simulations presented in this paper include the formation of sheared velocity flows, turbulent transport suppression by $\mathbf{E}\times\mathbf{B}$ flow shear, formation and growth of the H-mode pedestal, triggering of ELMs, and the dynamics of ELM crashes.

1. Introduction

Many different physical phenomena that interact over a wide range of spacial and time scales are needed for self-consistent modelling of the plasma edge in tokamaks. These phenomena include: The formation of poloidal and toroidal plasma flows; the quenching of the turbulent transport; the formation of edge and internal transport barriers where anomalous transport is sufficiently reduced so that neoclassical effects play an important role; the transition to an enhanced confinement mode; the triggering of Edge-Localized Modes (ELMs); and the recovery of plasma profiles after an ELM crash. A self-consistent model for simulations of plasma edge dynamics is needed to describe the formation of H-mode pedestal, the dynamics of an ELM crash, plasma relaxation after each crash, and the H-mode pedestal recovery. That model must include neoclassical and anomalous transport effects as well as neutral beam particle dynamics. The focus of this paper is the application of a self-consistent kinetic-MHD model in plasma simulations to investigate the dynamics of pedestal evolution and ELM crashes in order to optimize tokamak performance. The prediction of the instabilities that drive ELM crashes and the development of mechanisms for their mitigation are among the most challenging issues for whole device tokamak plasma modeling.

In this study, the formation and growth of the H-mode pedestal is simulated using the kinetic XGC0 code [1]. The XGC0 code can accurately compute the neoclassical effects and plasma flows that are important in self-consistent simulations of the plasma edge region where the turbulence is strongly reduced due to the strong $\mathbf{E} \times \mathbf{B}$ flow shear. XGC0 is a highly efficient, massively parallel kinetic neoclassical particle code, which can simulate the entire plasma volume during the time scale of the experimentally observed pedestal growth and ELM cycles. The XGC0 code conserves the energy and momentum during particle collisions as well as simplified ionization and charge exchange interactions in a Monte Carlo neutral particle transport model. The evolution of the radial electric field is evaluated self-consistently with particle dynamics. Magnetic field ripple can also be included for an evaluation of ripple induced transport of fast ions. The formation of an H-mode pedestal and the development of strongly sheared radial electric field profiles after the L-H transition have been demonstrated in XGC0 simulations [1]. It has also been shown that the pedestal width scaling has a built-in neoclassical component as a baseline mechanism.

The peeling-ballooning stability conditions are monitored using the ELITE code [4] to compute ideal MHD stability. When the peeling-ballooning triggering conditions for an ELM crash are satisfied in the simulations presented in this paper, the plasma profiles computed by XGC are imported into the extended non-linear MHD NIMROD code [2, 3] in order to follow the dynamics of an ELM crash. NIMROD simulation results for the growth and nonlinear evolution of the instability that results in an ELM crash are presented and discussed below. Simulation results presented in this paper for the H-mode pedestal buildup and ELM dynamics in DIII-D geometry indicate that diamagnetic rotation can strongly distort the filamentary structure of ELMs and can reduce the severity of an ELM crash. Consequently, it is found that the neoclassical effects included in the XGC0 code play a significant role in the dynamics of ELM crashes.

First principles physics associated with neutral beam injection (NBI) was not included in previous XGC0 code simulations. Instead, simplified momentum, particle, and heat fluxes were used at the inner boundary of the simulation domain. Many experimental observations indicate that the torque associated with NBI leads to additional toroidal rotation, which affects the level of saturated turbulence and associated anomalous transport, as well as the structure of the H-mode pedestal. A recent extension of the XGC0 code, which includes implementation of the beam geometry package from the NTCC NUBEAM module [5], is described in this paper. The NUBEAM module has been verified against other NBI codes [6] and validated against experimental data from a large number of tokamak discharges.

This paper is organized as follows: The results of coupled XGC/NIMROD simulations are presented in the Section 2 where FLR and two-fluid effects are discussed. New developments related to the implementation of neutral beam physics and self-consistent anomalous drift-wave transport models in the XGC0 code are described in Section 3. Research and code advancements are summarized in Section 4.

2. Kinetic-MHD modeling of an ELM cycle

Recently, the extended non-linear MHD code NIMROD [2, 3] has been be coupled together with the kinetic XGC0 code. The NIMROD code uses a high-order finite element representation that provides the necessary accuracy for MHD instability simulations. This representation also allows for strong transport anisotropy with realistic parameters. The NIMROD code is routinely used for plasmas with Lundquist numbers larger than 10^8 and for plasmas with very anisotropic heat fluxes, as indicated by the ratio of parallel and perpendicular transport coefficients $\chi_{\parallel}/\chi_{\perp} > 10^9$. A combination of leap-frog advance and semi-implicit methods for MHD terms makes it possible to resolve the multiple time-scale physics from ideal MHD (μs) time scales to transport (ms) time scales.

Numerous verification studies have been carried out in which NIMROD results have been compared with the results of other MHD codes as well as analytic scalings [7, 8]. In order to assure that the growth rates and peeling-ballooning stability thresholds found with the ELITE code qualitatively agree with the stability threshold found with the NIMROD code, the two MHD codes have been benchmarked against each other for a sample equilibrium from a Center for Plasma Edge Simulation (CPES) coupled kinetic-MHD study [9, 10]. An equilibrium that is based on DIII-D discharge 113317 was selected for the comparison. The growth rates as a function of toroidal mode number computed with the NIMROD and ELITE codes are shown in Fig. 1. In this example, the growth rates computed by NIMROD are approximately two times higher than the growth rates computed with the ELITE code, and the peeling-ballooning threshold computed with NIMROD is lower. The differences in results can be explained by differences in the resistivity profiles in ELITE and NIMROD. The ELITE code is an ideal MHD code with zero resistivity in the plasma core and infinite resistivity in the vacuum region. For linear NIMROD runs, the resistivity in the "vacuum" region is up to 1×10^6 larger than in the core plasma, approaching the ideal limit. For the free-boundary simulations, the resistivity has the Spitzer temperature dependence $T^{-3/2}$. For the DIII-D simulations shown here, the temperature ratio between the core and edge is approximately 500, which yields a resistivity ratio of approximately 10^5. For simulations with lower resistivities in the plasma region and higher resistivities in the vacuum region, NIMROD yields results that are in better agreement with the ELITE results. Despite the differences in the growth rates, the eigenfunctions computed with NIMROD and ELITE agree reasonably well [11]. This makes it possible to use the NIMROD code for nonlinear evolution studies of ELM crashes and to use the ELITE code, which is better validated against the experimental data, for the linear peeling-ballooning stability analysis of plasma profiles computed with the XGC0 kinetic code.

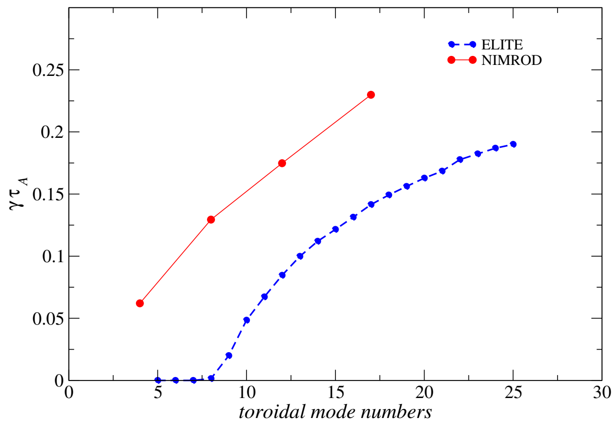

FIG. 1. Growth rates as a function of toroidal mode number computed with the NIMROD and ELITE codes for the DIII-D discharge 113317.

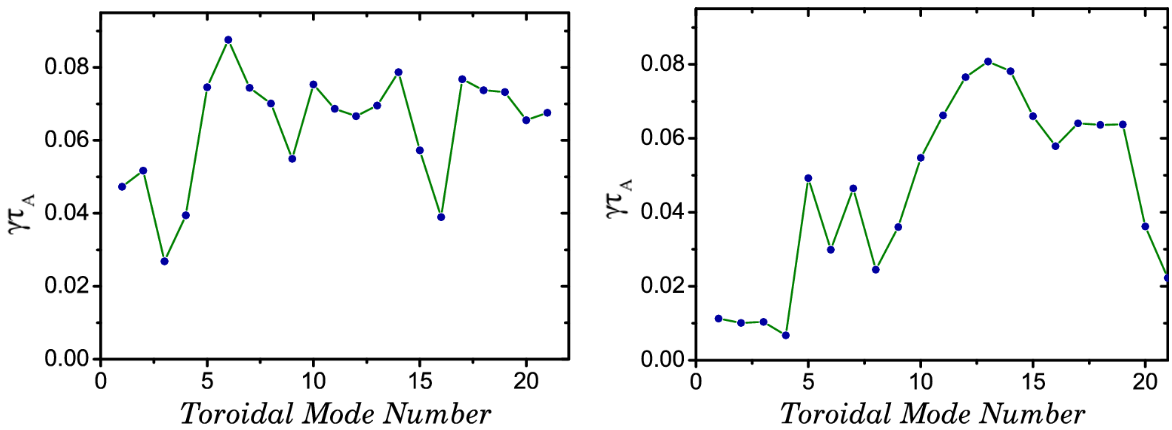

FIG. 2. The growth rates as function of toroidal mode numbers computed in the NIMROD simulations of ELM unstable equilibrium for the DIII-D discharge 96333 without two-fluid effects (left panel) and with two-fluid effect (right panel).

The dynamics of ELM crashes in several DIII-D discharges have been studied using coupled XGC0/NIMROD simulations. In these coupled simulations, the linear ideal MHD stability code ELITE is used to identify if an equilibrium is unstable to a peeling or ballooning mode that can develop into an ELM crash. If the ELITE code finds a mode with a linear growth rate that is above the typical threshold for ELM instability (usually taken to be one half of the ion diamagnetic drift frequency), then the corresponding kinetic equilibrium is transferred to the NIMROD code in order to carry out a simulation of the nonlinear evolution of the ELM crash. In these nonlinear NIMROD simulations of DIII-D discharges, it has been shown that the dynamics of an ELM crash is strongly affected by two-fluid effects. These effects are represented by the gyro-viscous and Hall terms that have been recently implemented in the generalized Ohm's law and in the momentum equation in the NIMROD code [12, 13, 11]. The two-fluid effects tend to stabilize high mode numbers [13]. The stabilization of the high-n modes, which have a relatively fine spatial scale, should make the corresponding nonlinear computation easier. Two-fluid effects on the growth rates are demonstrated in Fig. 2, in which the growth rate is plotted as a function of toroidal mode number for NIMROD computations with and without two-fluid effects included. The two-fluid effects cause the modes to rotate with a poloidal drift frequency comparable to the diamagnetic frequency, and this mode rotation makes it more difficult to advance the equations in time. It is shown in Fig. 3 that the ELM filaments are strongly sheared by diamagnetic effects in the H-mode pedestal region. Such shearing will influence the heat load associated with ELM crashes and might significantly increase the propagation time of ELMs through the pedestal region.

3. Implementation of effects of non-thermal particles and anomalous transport in the XGC0 code

Turbulence-driven transport is modeled in XGC0 as a radial random walk diffusion of particle orbits with diffusivity computed using a predictive transport model. Either the GLF23 gyro-Landau-fluid model or the Multi-Mode fluid based drift-wave transport model can be utilized in XGC0 code simulations using an interface that was created as a part of the Framework for Modernization and Componentization of Fusion Modules (FMCFM)

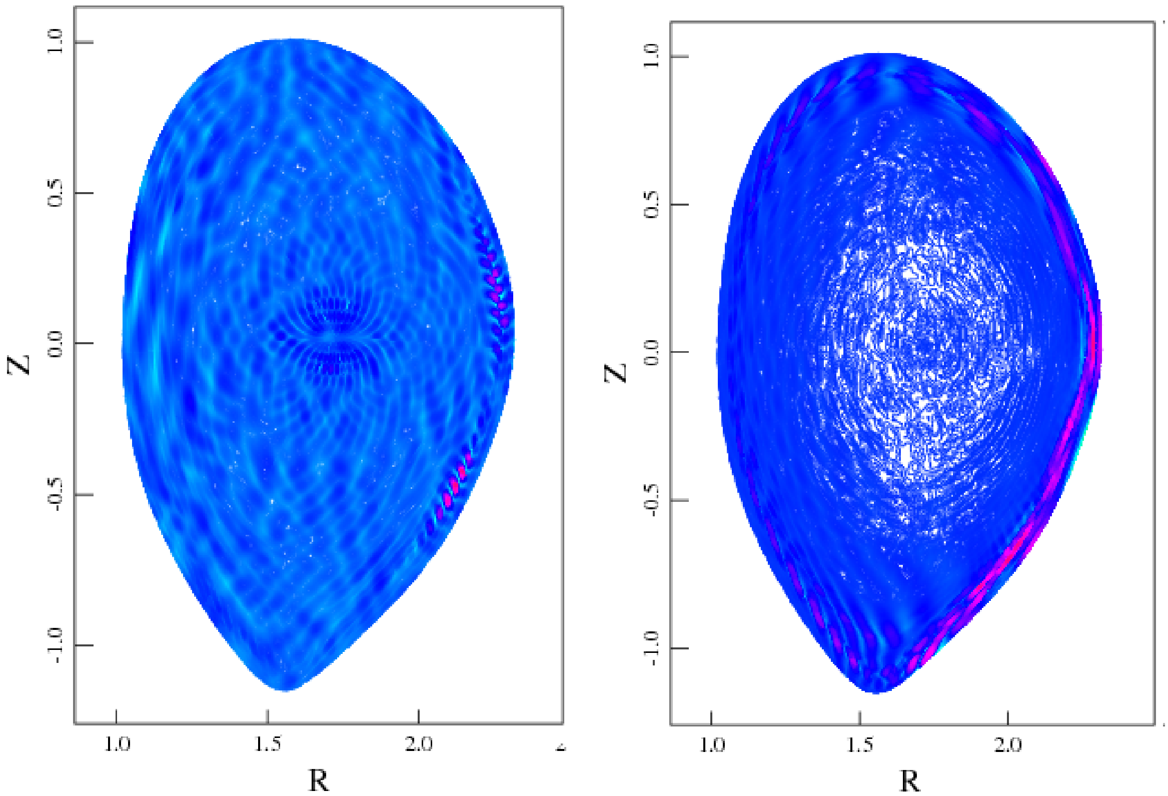

FIG. 3. Contour plots of the electron temperature perturbation during an ELM crash computed with the NIMROD code for the DIII-D discharge 96333. The code is initialized with an ELM unstable equilibrium computed from the plasma profiles that are advanced with the XGC0 code. The left panel shows the electron temperature perturbation contour plot during the linear stage of a ballooning instability that leads to an ELM crash; the right panel corresponds to the nonlinear stage of the ELM crash, when the ELM filaments are sheared by the diamagnetic effects in the poloidal direction.

project. The dynamic evolution of the plasma edge region is seen in self-consistent simulations carried out using the XGC0 code. These simulations include the formation of sheared velocity flows and $\mathbf{E} \times \mathbf{B}$ flow shear (for example, see Fig. 4), turbulence transport suppression, and formation of an H-mode pedestal. The XGC0 code includes several models that take into account the $\mathbf{E} \times \mathbf{B}$ flow shear effect on the anomalous transport. These reduced models are based on the idea of turbulent transport suppression similar to the Hamaguchi-Horton model [14] and the Hahm-Burrel model [15]. The flow shear effect can be directly included in the MMM95 and GLF23 models by taking into account the $\mathbf{E} \times \mathbf{B}$ flow shear rates in the computation of ITG and TEM growth rates. Self-consistent particle and thermal diffusivities computed with the GLF23 model are shown in Fig. 5. The anomalous transport is significantly nonuniform in the pedestal area. The anomalous transport leads to the relaxation of plasma profiles toward marginally stable profiles. This conclusion becomes evident by comparison of the left and right panels in Fig. 5, which correspond to the diffusivity profiles at the beginning and at the end of the simulation. The particle diffusivities are typically smaller than the thermal diffusivities during the simulation. The electron diffusivity profiles exhibit a similar behavior.

The XGC0 code takes into consideration the effects of background neutrals [1]. The

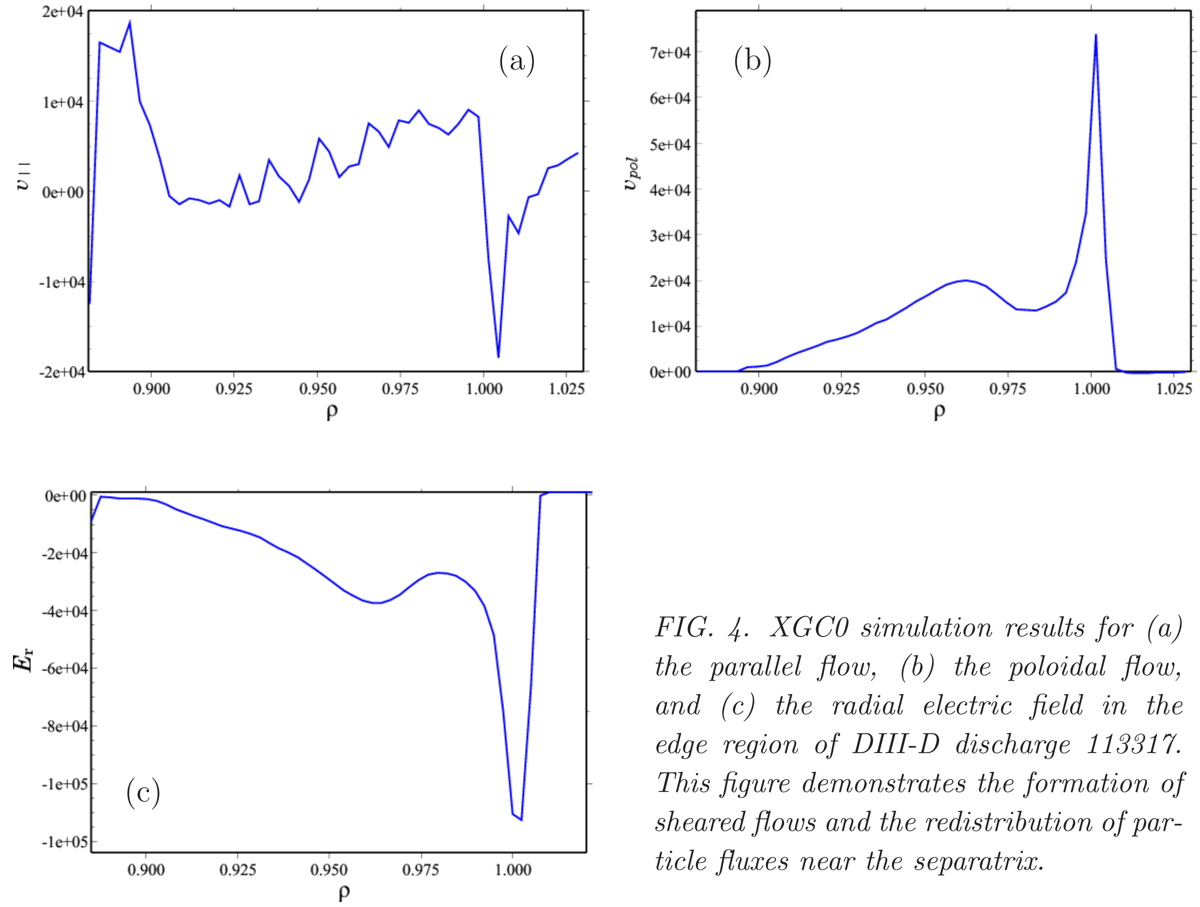

FIG. 4. XGC0 simulation results for (a) the parallel flow, (b) the poloidal flow, and (c) the radial electric field in the edge region of DIII-D discharge 113317. This figure demonstrates the formation of sheared flows and the redistribution of particle fluxes near the separatrix.

neutrals start outside of the separatrix from a prescribed birth surface with a Maxwellian velocity distribution at the Franck-Condon temperature. The neutrals model takes into account charge exchange, ionization, and elastic collisions. In the current study, the model for background neutrals is extended to include fast neutrals that are generated by the neutral beam injection. In this new model for non-thermal neutrals, no assumption is made about the distribution function of fast neutrals. The velocities of incoming neutrals are individually computed in the beam geometry module NBLINE, which was originally developed as a part the National Transport Code Collaboration (NTCC) [16] NUBEAM module [5]. The NUBEAM beam geometry package supports multiple neutral beams with individual geometries, including different shapes for the ion sources, and the package takes into account realistic beam compositions. The straight line tracker from the NUBEAM module, XSTRALN, is used to track neutrals up to the point where they enter the plasma. The NTCC Plasma State module is used to access the beam geometry information and beam voltages. The Plasma State module provides access to an extensive database of NBI geometries for different tokamaks. Individual beam powers, which are generally functions of time, are provided through the XGC0 namelist.

In the NBLINE module, neutrals are started with random angles at the injector plate and they are tracked to the tokamak plasma edge. The horizontal and vertical divergences of the neutral beams are taken into account. Once the neutrals enter the plasma, they are handled by the model for neutrals in the XGC0 code. The NBI equilibrium distribution

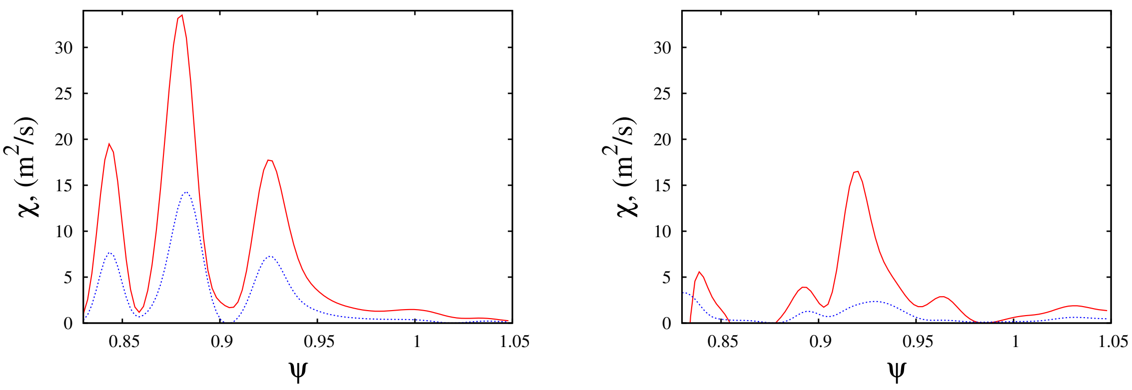

FIG. 5. Thermal and particle ion diffusivities computed with the drift-wave GLF23 transport model from the FMCFM interface in the XGC0 code. The diffusivities are shown after the first time step in the left panel, and the diffusivities are shown close to the end of the simulation. The thermal diffusivities are shown as solid curves and particle diffusivities are shown as dotted curves.

function is evaluated for a fixed kinetic background for several time slices using a "goosing" technique that is used in the NUBEAM module. This technique is used in order to accelerate the collision and charge exchange operators artificially so that only selected orbits are evaluated for each specific time slice. In this way, one can account for the slow process of neutral beam slowing on the fast kinetic time scale. The non-thermal particles that are generated with the NBLINE module are involved in the same atomic processes as the background neutrals. However, because energies of non-thermal neutrals are much higher than energies of background neutrals, the cross section tables that are used in the XGC0 code will need to be updated. The NTCC PREACT module will be implemented in the XGC0 code and will provide access to the cross-sections over the range of energies that are applicable to the neutral beam particles.

4. Summary

ELMy H-mode DIII-D discharges are studied with a self-consistent numerical model that includes coupled kinetic-MHD simulations and ideal MHD stability analysis. The formation and growth of the H-mode pedestal are simulated using the kinetic XGC0 code. The peeling-ballooning triggering conditions for ELM crashes are monitored with the ELITE linear stability code. ELM crash dynamics are modeled with the extended nonlinear MHD NIMROD code. In the coupled XGC0/NIMROD simulations of an ELM cycle in DIII-D geometry, it is demonstrated that two-fluid and FLR effects can significantly change the spectrum of unstable ballooning modes and the dynamics of an ELM crash. As a result of diamagnetic effects, the ELM filaments become strongly sheared in the poloidal direction for the DIII-D discharges studied in this paper.

New developments in the XGC0 code are described, which include the implementation of the beam geometry package from the NTCC NUBEAM module as well as the FMCFM interface to anomalous transport models. The NBLINE beam geometry module that was originally developed as a part of the NTCC NUBEAM module has been implemented in the XGC0 code. The non-thermal neutrals are followed from the beam source to the plasma with the straight line tracker XSTRALN module. The XGC0 cross-sections need to be updated with the NTCC PREACT module because of the fast and thermal energy spectra.

The Framework for Modernization and Componentization of Fusion Modules (FMCFM) is implemented in the XGC0 code. The FMCFM interface provides access to drift-wave anomalous transport models such as GLF23 and MMM95. It is shown that while the turbulence might be strongly reduced by the strong $\mathbf{E} \times \mathbf{B}$ flow shear, the anomalous transport remains significantly nonuniform in the pedestal region. Due to the anomalous transport, plasma profiles relax toward the marginally stable profiles. It is found that the particle diffusivity is typically smaller than the thermal diffusivity in these simulations.

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