**Integrated simulations of energetic particle transport in burning plasmas**

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Energetic particle (EP) transport is a critical component of burning plasma physics. The energetic fusion product alpha particles provide the dominant source for heating and sustaining burning plasmas. However, these energetic alpha particles, together with energetic neutral beam ions, can resonantly drive Alfven instabilities leading to alpha particle redistribution and losses. Anomalous alpha transport and losses can potentially degrade alpha particle heating and damage the reactor first wall. Therefore it is crucial to understand and control alpha particle transport in a burning plasma.

Integrated simulation of multi-scale and multi-physics is required to determine EP transport and assess the EP interaction with thermal plasmas. For example, kinetic effects of finite ion gyroradius of thermal ions are needed for the radiative damping, one of important damping mechanisms of EP-driven Alfven eigenmodes. Thus, an accurate calculation of their stability threshold requires resolution of multiple spatial scales ranging from plasma minor radius to thermal ion gyroradius. Furthermore, one needs to resolve multiple time scales for proper modeling of nonlinear evolution of EP-driven Alfven mode and EP transport. The time scales range from the fast scale of the Alfven wave period to the slow scale of EP slowing-down and pitch angle scattering. Finally, a variety of 3D perturbations can impact EP transport including sawteeth, tearing mode, Alfven eigenmodes and plasma micro-turbulence in plasma core and ELM, RMP, and toroidal field ripple in plasma edge. Thus modeling of global EP transport requires integration of multiple modes and multiple physics.

Energetic particle physics is a key and integral component of Whole Device Modeling (WDM) because EP effects are essential for plasma equilibrium, stability and transport. First, EPs provide one of the main sources for plasma heating, current drive, and plasma rotation. Second, EPs can have strong effects on MHD modes such as sawteeth, tearing modes, and resistive wall modes. Finally EPs can significantly impact thermal plasma transport via EP-driven modes. Therefore integrated simulation of EPs is an essential element of WDM.

Similarly, EP effects are important for the physics of plasma disruption. EP effects are important for onset of plasma disruption. For example, stabilizing effects of EPs can lead to giant sawteeth and triggering of neoclassical tearing modes that may eventually lead to disruption. EPs can also substantially affect stability of MHD modes such as tearing modes and RWM. Furthermore, EPs can affect plasma disruption indirectly via their effects on plasma equilibrium.

Substantial progress has been made in simulation of EP-driven modes and EP transport since ReNew workshop in 2009. Major advances include gyrokinetic simulations of EP-driven Alfven modes in current tokamaks and ITER, hybrid simulations of energetic particle interaction with MHD modes, hybrid simulation of EP-driven Alfven instability with particle collisions and particle sources, and development of new reduced models such as the critical gradient model and the quasilinear model for energetic particle transport. Despite these important advances, much work remains to be done for building a predictive integrated simulation model of energetic particle transport. This is a challenging task due to multiple scales and strong sensitivity of the problem to plasma parameters and profiles such as the safety factor profile. Towards this goal, we propose the following initiatives including verification and validation of EP simulation models, method of integrated simulations of multi-scale and multi-physics, and simulations of runaway production and transport.

(1)Develop methods for integrated simulation of EP transport

Integrated simulation methods need to be developed for EP-driven Alfven instabilities and EP transport. We need to determine EP transport due to multiple 3D perturbations including MHD modes, Alfven eigenmodes, and external 3D perturbations. In particular, we need to bridge multiple time scales ranging from the fast Alfven time to the slow confinement time. It is very difficult to carry out long time simulations of EP transport using the first-principle-based gyrokinetic model due to its prohibitive computational cost. One way to bridge the multiple time scale is developing reduced simulation models that describe the slow evolution of mode amplitude and EP profile. One such model is the quasi-linear model recently developed for EP transport. Another way is combing appropriately the first-principle models and reduced models for the long time transport simulation. The initial fast onset and saturation phase can be modeled with a first-principle model while the slow quasi-steady state phase can be treated with a reduced model. A third approach is to use gyrofluid closure models, which can be extended to include many of the same mechanisms as the more complete models, but at a lower computational cost. These approaches have to be verified and validated (or VV). An important element of VV is studying the extent to which the reduced models are justified in applications to the experiments.

(2)Code Verification and Validation

Substantial progress has been made in code verification and validation since 2009. However much remains to be done for establishing a predictive simulation model of EP transport in present day tokamak experiments and future fusion reactors such as ITER and DEMO. A more systematic and careful code verification and validation needs to be carried out for linear damping mechanisms and stability threshold of Alfven modes although considerable progress has been made in this regard. Even more important is code verification and validation for nonlinear mode evolution and EP transport. In particular, substantial effects are required for code verification through code to code comparison and code benchmark with analytic theory if available. Considerable efforts are also needed for code validation with respect to linear stability, nonlinear dynamics and EP transport. The task of code verification and validation is a long time process and should be done in parallel with development of integrated simulation model and analytic theory. It should be noted that analytic theory is one of the essential elements needed for physics understanding and code verification.

(3)Simulations of runway confinement with 3D MHD perturbations and whistler waves

The relativistic runaway electrons generated post plasma disruption can potentially damage the first wall of ITER due to their high energy content. Thus it is an extremely important problem for machine safety. The physics of runaway is a new area of research for energetic particle physics and has received much attention recently.

An important problem of runaway is its interaction with 3D MHD modes, pellet ablation clouds, and high frequency whistler waves. Much work needs to be done to understand the effects of runaway on plasma stability and the effects of MHD perturbations and whistler waves on runaway confinement. Specifically we need to assess how MHD instability and whistler waves affect self-consistently the generation and confinement of runaway. An integrated simulation model needs to be developed to resolve the multiple time scale range from fast MHD and whistler oscillations to slow equilibrium evolution. One possible approach is a fluid model for describing runaway interaction with MHD modes together with a kinetic closure for runaway generation. The interaction of runaway with whistler waves must be treated kinetically and its effects on runaway distribution can be coupled to MHD equations via kinetic closure.

In summary, Energetic particle (EP) transport is a critical component of burning plasma physics. Integrated simulation of multi-scale and multi-physics is required to determine EP transport and assess the EP interaction with thermal plasmas. Energetic particle physics is a key and integral component of Whole Device Modeling (WDM) and plasma disruption simulation. Initiatives are proposed for developing methods of integrated simulation with multiple scales, for code verification and validation, and for integrated simulation of runaway.