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Burning Plasma Transport Simulation for Axisymmetric Tokamaks with Alpha-Particle Heating

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The primary goal of Tokamak based fusion reactors is to achieve a self-sustained plasma satisfying ignition criterion by maximizing the product of plasma density, temperature and energy confinement time. There are limits on achievable plasma density and temperature due to current driven or pressure driven instabilities. Also, the Tokamak performance can be enhanced by operating with advanced configurations and it is necessary to study them extensively to maintain specific profile of plasma parameters. The understanding and controlling of the energy confinement time and plasma profiles fall in the domain of plasma transport. In self-sustained Tokamak based fusion reactors, the plasma heating will be mainly carried out by the alpha-particles that are produced in the fusion of deuterium and tritium. It is thus necessary to study the burning plasma performance with plasma heating due to alpha-particles. This study is aimed at finding the optimal power deposition due to alpha-particles required to maintain a particular plasma profile, for which we have developed a 1.5-dimensional self-consistent transport model. We present a qualitative comparison of the results of this model with experimental results and results of other models of TFTR {1}, JET {2} and ITER-like {3} cases. We also present our simulation results for SST-2-like {4} case.

To perform a burning plasma transport simulation, it requires to solve continuity equations, energy equations, Ohm's Law and Maxwell equations. The steady state momentum equation to simulate plasma equilibrium that includes alpha-particle physics is coupled with this model. The plasma equilibrium is considered as fixed-boundary equilibrium and the boundary is defined by a set of points that define the plasma shape. In this study, transport equations are considered in the flux co-ordinates and the plasma configuration is assumed to be toroidally axisymmetric. The continuity and energy equations used in our model are {5}:

$$\frac{\partial\langle n_i\rangle}{\partial t} = -\frac{1}{V'}\frac{\partial}{\partial\rho}(V'\Gamma_i) + \left[\frac{dn}{dt}\right]_{iz} + \left[\frac{dn}{dt}\right]_{fus}$$

$$\frac{\partial\langle n_n\rangle}{\partial t} = -\frac{1}{V'}\frac{\partial}{\partial\rho}(V'\Gamma_n) - \left[\frac{dn}{dt}\right]_{iz}$$

$$\frac{\partial p_i}{\partial t} = -\frac{2}{3V'}\frac{\partial}{\partial\rho}\left(V'\left(q_i + \frac{5}{2}T_i\Gamma_i\right)\right) + P_{\alpha i} + P_{coll}$$

$$\frac{\partial p_e}{\partial t} = -\frac{2}{3V'}\frac{\partial}{\partial\rho}\left(V'\left(q_e + \frac{5}{2}T_e\Gamma_e\right)\right) + P_{\alpha e} - P_{coll} + P_{ohm} - P_{rad} + P_{aux}$$

Here, ρ is flux coordinate, $\langle f\rangle$ denotes flux-surface average of f, t is time, V is volume within a flux-surface, Γ_i is ion flux, Γ_e is electron flux, Γ_n is neutral particle flux, $\langle n_i\rangle$ is flux-surface averaged ion density, $\langle n_n\rangle$ is flux-surface averaged neutral particle density, p_i is ion pressure, p_e is electron pressure, T_i is ion temperature, T_e is electron temperature, q_i is ion heat flux, q_e is electron heat flux, $[dn/dt]_{iz}$ is rate of change of density due to ionization, $[dn/dt]_{fus}$ is rate of change of density due to fusion, $P_{\alpha i}$ is power per unit volume due to alpha-particle heating for ions, $P_{\alpha e}$ is power per unit volume due to alpha-particle heating for electrons, P_{coll} is power per unit volume due to ion-electron collisions, P_{ohm} is Ohmic power per unit volume, P_{rad} is power per unit volume due to radiation, P_{aux} is power per unit volume due to auxiliary heating. We assume quasi-neutrality for electron density.

We model alpha-particle heating $P_{\alpha i}$ and $P_{\alpha e}$ by solving the Fokker-Planck equation for alpha-particles. We find that energy-loss characteristic time for 3.5 MeV alpha-particles is ˜1s, which corroborates solving for its energy-loss equation along with transport simulation. We assume Bremsstrahlung radiation loss to be the dominant mechanism among radiation losses and ignore other mechanisms.

The transport equations are solved using LCPFCT {6}, which uses the explicit algorithm FCT (Flux-Corrected Transport). Important features of FCT are that it is conservative and maintains positivity and monotonicity. For our purpose we use a modified version of LCPFCT that is compatible with flux co-ordinates. To solve Grad-Shafranov equation, we use VMOMS {7}, which uses a variational moment method that expands radial co-ordinates as Fourier series in flux co-ordinates and solves the resulting equations using Shooting method for a closed boundary system in 2-dimensions. We use an empirical mixed Bohm/gyro-Bohm model {8} to find the particle and heat fluxes for ions and electrons.

In our simulations, total runtime consists of several energy confinement times. We start with ramp-up of plasma by evolving its LCFS and heat with auxiliary heating until alpha-particle heating dominates the plasma heating. Plasma is then maintained at a plateau region, where its LCFS is not further evolved. We observe formation of edge pedestals, which are characteristics of H-mode Tokamaks. For a snapshot of a typical ITER-like case at its plateau region, alpha-particle heating profile obtained from our alpha-particle heating equation is shown in figure below.

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