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Dynamic Modeling of Multi-channel Transport Bifurcations Using Ion Temperature Gradient Based Models for Tokamak Plasmas*

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Abstract. Rotational shear stabilization is believed to play a major role in the formation of core transport barriers in tokamak plasmas. However, dynamically following bifurcations in the particle, energy, and momentum confinement that lead to the formation of transport barriers with the most sophisticated theoretical models remains an important yet unresolved numerical problem. In DIII-D VH-mode and NCS discharges, it has been argued that $E \times B$ rotational shear induced by a momentum channel bifurcation is the most likely cause of the observed core transport barrier. In DIII-D, diamagnetic rotational shear stabilization induced heat flow bifurcations have been proposed as a mechanism for the L/H transition. This mechanism is of particular interest since a pessimistic power threshold is predicted at smaller values of normalized gyroradius ρ_*. In previous studies by Staebler *et al.*, simple heuristic models were used to examine multi-channel bifurcations. In this work, we consider the GLF23 gyro-fluid based transport model which contains both heat flux and momentum bifurcation mechanisms. Using the GLF23 model, we explore various numerical techniques in order to successfully allow time-dependent transport codes to dynamically follow bifurcations to enhanced confinement regimes by self-consistently computing the effect of $E \times B$ shear stabilization. Successful implementation of numerically robust algorithms will allow determination of power threshold scalings for core transport barriers and the L/H transition.

I. INTRODUCTION

A paradigm that has emerged suggests that $E \times B$ shear stabilization of anomalous transport in tokamaks can lead to improved core confinement and is the leading candidate to explain reduced core transport in negative central shear (NCS) or reversed shear (RS) discharges, supershots, and optimized shear (OS) discharges [1–5]. Considerable success has been achieved in previous work using phenomenological models to reproduce the qualitative features of transport bifurcations. The goal of this work is to advance predictive modeling capability by improving on existing code technology to allow numerically robust modeling of bifurcation phenomena with stiff critical gradient models.

II. TRANSPORT BIFURCATION MECHANISMS

Several key elements have been identified in playing a role in the formation of internal transport barriers including $E \times B$ rotational shear stabilization, Shafranov shift or α-stabilization, magnetic shear, and T_i/T_e. Under certain conditions, these effects can trigger a bifurcation in the momentum, thermal, and/or density transport. While it is instructive to examine the dynamical properties of bifurcations using simple heuristic models and focus on a single channel, the truely multi-channel nature of the problem

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warrants study using the most comprehensive physics-based models. Here, we focus on studying thermal and toroidal momentum bifurcations and numerical techniques necessary to successfully follow dynamic transitions using the GLF23 transport model [2].

The GLF23 model [2] is a 1-D dispersion type transport model developed from 3D gyro-kinetic stability calculations for the linear growth rates and from 3D nonlinear gyro-Landau-fluid simulations to determine the saturation levels. This critical gradient drift-ballooning mode based model yields quasi-linear estimates of the density, thermal, and momentum transport and includes turbulence suppression mechanisms of $E \times B$ rotational shear, α–stabilization, and magnetic shear. Another distinguishing feature of this model is that it includes the physics of the electron temperature gradient (ETG) mode which has been found to be important for predicting the observed anomalous levels of electron thermal transport found in many DIII-D discharges exhibiting suppressed ion thermal transport in the core region. It can be characterized as a "stiff" model in that relatively large amounts of input power are required to drive the model away from marginality.

III. DYNAMIC MODELING OF CORE TRANSPORT BARRIER FORMATION

Considerable success has been achieved in previous work using phenomenological models to reproduce the qualitative features of transport bifurcations [6–8]. In Fig. 1, the dynamic formation of an internal transport barrier resulting from an $E \times B$ shear driven bifurcation is demonstrated using the GLF23 model for a DIII-D NCS discharge with an L-mode edge [9]. Shown is the predicted ion temperature and toroidal velocity at various radii versus simulation time.

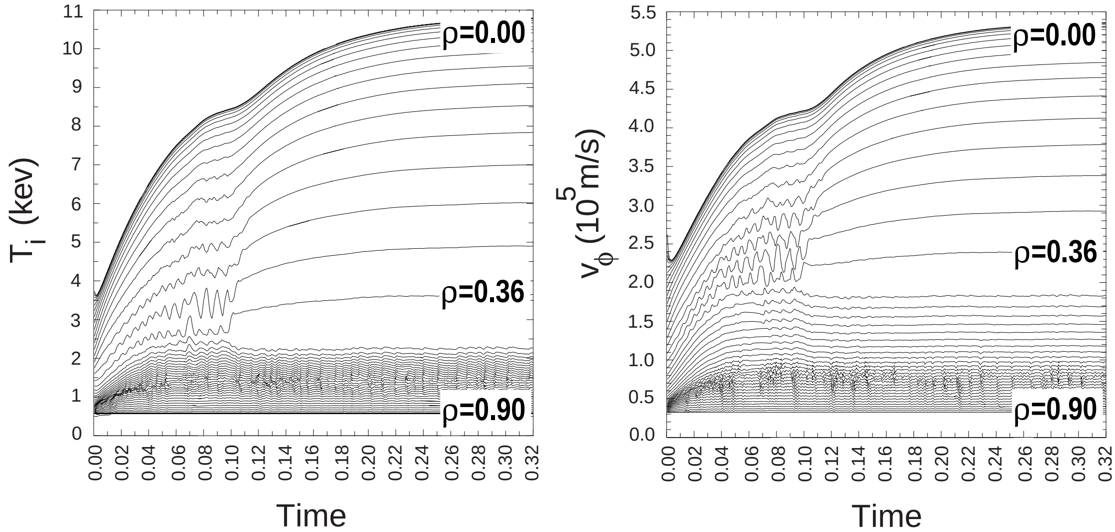

FIG. 1. Time evolution of ion temperature and toroidal velocity predicted by the GLF23 model for DIII-D NCS discharge #84736 at 1.30 s. Values are shown at various radii with an equal spacing in normalized toroidal flux of 0.02.

In the simulation, both the thermal and toroidal momentum transport were evolved while self-consistently computing the effects of rotational shear stabilization. Using the MLT code [10], the simulations were carried out taking sources, sinks, equilibrium, and the density profile from a power balance analysis with experimental boundary conditions enforced at a normalized toroidal flux of $\hat{\rho} = 0.9$. A multiplier of 1.1 on the $E \times B$ shear rate γ_E was needed to give a transition midway through the simulation and to yield temperature profiles consistent with the experiment. Here, we follow the prescription given in Ref. [2]

for $E \times B$ shear stabilization with $\gamma_E = (r/q)(\partial/\partial r)(qv_E/r)$ where the $E \times B$ velocity v_E is given by radial ion force balance

$$v_E = -\frac{E_r}{B} = v_{\theta i} - \frac{B_\theta}{B} v_{\phi i} - \frac{1}{en_i B_\phi} \frac{\partial P_i}{\partial r} \tag{1}$$

Here, $v_{\theta i}$ is computed using a collisionless neoclassical estimate [6]. For the DIII-D case studied, the neoclassical and diamagnetic terms are small in comparision with the toroidal term in the region where the ITG mode is unstable.

In examining the simulations we see that as γ_E approaches the maximum linear growth rate γ near $\hat{\rho} = 0.35$, the profiles begin to dither around this marginal point exhibiting an oscillatory behavior similar to that observed in simulations described in Ref. [8] using a heuristic model. The core T_i and v_ϕ profiles then begin to steepen inside the negative magnetic shear region. Finally, γ_E exceeds γ sufficiently that the plasma jumps from a dithering state to an enhanced confinement state and a sharp leading edge forms in the T_i and v_ϕ profiles. While $\gamma_E > \gamma_{\max}$ shuts off transport from low-k drift-ballooning modes, the electron thermal transport remains anomalously high due to the remaining presence of high-k ETG modes and their $\sqrt{m_i/m_e}$ larger growth rates. Figure 2 shows that for this particular case, the steady-state predicted temperature and toroidal velocity profiles agree with experimental data to within 20%.

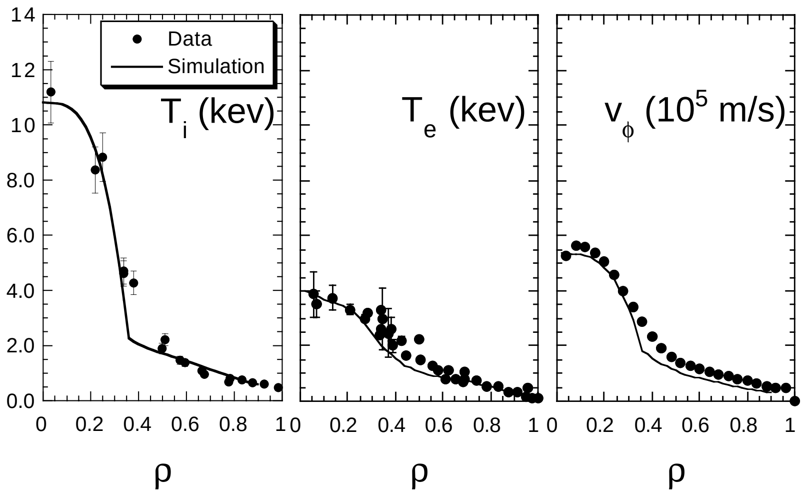

FIG. 2. Ion temperature, electron temperature, and toroidal velocity profiles from the GLF23 model at the end of the simulation compared against experimental data for #84736.

Also examined is the JET OS discharge #40847 using data from the ITER Profile Database [11]. Without evolving the toroidal momentum it is found that a multiplier of 2.65 is needed on γ_E to obtain agreement with the experimental temperature profiles. Figure 3 shows the simulation results where all terms in Eq. (1) are included with the toroidal velocity taken from the experiment. While the mode growth rates are comparable to DIII-D NCS discharges, the $E \times B$ shear rate is somewhat smaller in comparison.

IV. MODELING AND PHYSICS ISSUES

There are a number of critical physics and modeling issues associated with modeling bifurcations and barrier formation. First, several numerical issues are readily identifiable including: negative diffusivities, a large response from stiff models to small changes in profiles, the ∇P_i term in E_r, noisy source profiles, and noisy corrections to the measured carbon velocities.

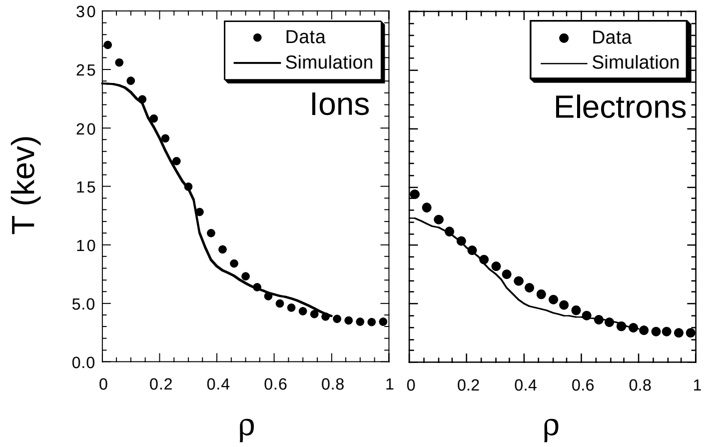

FIG. 3. Steady-state ion and electron temperature profiles from the GLF23 model compared against experimental data for JET OS discharge #40847 at 46.86 s.

Thus far, we find that the optimum choice of numerical techniques for handling stiff critical gradient models and dynamically predicting bifurcations includes combining under-relaxation (i.e. 10% $T_{\rm new}$ + 90% $T_{\rm old}$) with the DV method and time-steps on the order of 20 ms. The DV method specifies some variation in the ion temperature gradient by which to sample the model diffusivity and, by Taylor expansion, splits it into a diffusivity and a convective velocity. Here, sampling the diffusivity between ∇T_i and $\nabla T_i + 0.03\nabla T_i$ proved sufficient. The numerical approach is generalizable but some tuning is required on an individual basis. In future work, we plan to explore various adaptive grids and predictor-corrector methods to improve the efficiency and robustness of the simulations.

There are important physics issues with both the underlying transport and the prescription for $E \times B$ shear. For example, in this study it was discovered that for some NCS discharges the GLF23 model incorrectly predicted a transport barrier in the outer third of the plasma because γ_E was predicted to exceed the maximum linear growth rate γ in a region where γ was at a local minimum. For the JET OS discharges, the turbulent viscosity dropped to neoclassical levels just outside the ITB region when attempting to evolve the toroidal momentum causing a rapid increase in $E \times B$ shear and a second barrier to form. This behavior is believed to be the result of missing electromagnetic effects. In recent calculations made using a linear gyrokinetic code extended to include geometric effects via a local equilibrium model, it was found that electromagnetic effects can result in noticable increase in the ITG mode growth rate in the positive shear region where it would typically be stable or nearly stable in the electrostatic limit. However, these effects are not yet in the present model.

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