Progress on nonlinear MHD modeling of flux pumping and hybrid scenario for ASDEX Upgrade plasmas

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Based on recent ASDEX Upgrade (AUG) experiments focusing on the hybrid scenario and sawtooth control [3], this theoretical work presents a first quantitative simulation study of flux pumping at experimental conditions with the nonlinear, two-temperature, full magnetohydrodynamic (MHD) model in JOREK [1]. We incorporate experimental profiles of equilibrium, current source, etc., and realistic parameters, such as Spitzer resistivity and viscosity. Simulations on the long resistive diffusion timescale of seconds validate the effectiveness of the 1/1 core MHD instability induced dynamo effect in flux pumping and sawtooth suppression. Simulated evolutions of the central safety factor (q_0) and current density are consistent with the reported AUG experiments [3]. We carefully analyze the self-regulating behavior of core plasma during flux pumping, which is characterized by anomalous redistribution of current density and magnetic flux due to the dynamo effect [4].

The modeling work on flux pumping is primarily motivated by the high design priority of sawtooth control for next-generation reactor-scale tokamaks [5], such as ITER and DEMO. Avoiding giant sawtooth is crucial for preventing neoclassical tearing modes (NTMs) induced disruptions, thus is beneficial in sustaining long-pulse discharges and improving plasma confinement. In this context, flux pumping observed in the hybrid scenario serves as a promising candidate to meet these requirements [4, 6]. Compared with the conventional inductive H-mode scenario and the fully non-inductive reversed shear scenario [5], flux pumping can maintain robust, broad, and shear-free profiles of safety factor (q) and current density in the plasma core through the self-regulation of plasma, thereby clamping q_0 around unity and preventing the further sawtooth onset.

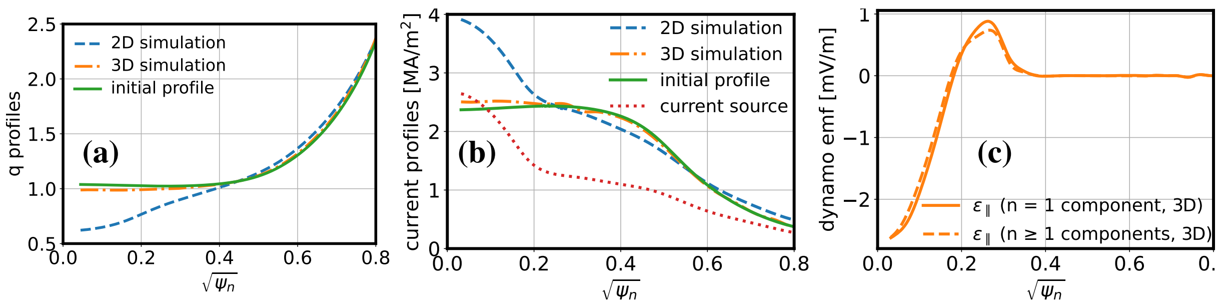

Figure 1. (a) q and (b) current density profiles at the initial stage (solid), saturated stages of 2D (dashed) and 3D (dash-dotted) simulations; dotted line in (b) represents the non-inductive current source. (c) Dynamo electromotive forces (emf) along the mean magnetic field from the 3D simulation, respectively calculated with n = 1 component (solid) and all n $\geq$ 1 components (dashed). For direct comparison, q and current density profiles for AUG experiments can be found in Figs. 3-4 in Ref. [3].

Main simulation results for the flux pumping phase of AUG discharge #36663 [3] are presented in Fig. 1. First, a 2D simulation is conducted, excluding MHD instabilities but considering the non-inductive current source. The latter is equal to the sum of NBI (Neutral Beam Injection), ECCD (Electron Cyclotron Current Drive), and bootstrap current, as shown by the dotted line in Fig. 1 (b). The saturated q profile from the 2D simulation is plotted by the dashed line in Fig. 1 (a), with q_0

eventually decreasing to 0.6. Such a q_0 value below unity typically suggests sawtooth instability, which contradicts the experimental observation (sawtooth-free). In contrast, the 3D simulation with dominant 1/1 MHD activity shows that the saturated q_0 remains around unity in the plasma core, as shown by the dash-dotted line in Fig. 1 (a). The further comparison of toroidal current density in Fig. 1 (b) confirms the above discrepancy in q profiles. In 2D simulation, the central current density increases from 2.4 MA/m^2 to 4 MA/m^2. However, in the 3D simulation, it is clamped around 2.5 MA/m^2, suggesting an anomalous redistribution of current density. The saturated q profile and toroidal current density from the 3D simulation align well with the experimental equilibrium reconstructed with IMSE (Imaging Motional Stark Effect) data ($q_0 \simeq 1.0$ and $J_{\mathrm{tor}} \simeq 2.5$MA/m^2, see Figs. 3-4 of Ref. [3]) during the flux pumping phase, where the plasma core remains almost stationary and free of sawtooth. The results highlight the critical role of core MHD instabilities in the current redistribution.

The anomalous current redistribution mainly results from the MHD dynamo effect induced by the 1/1 MHD instability [4], which exhibits combined characteristics of 1/1 quasi-interchange mode and 1/1 tearing mode. As shown by Fig. 1 (c), the dynamo electromotive force (emf) along the axisymmetric magnetic field ($\mathbf{b}_{n=0}$) is mainly generated by n = 1 non-axisymmetric components of plasma velocity $\tilde{\mathbf{v}}$ and magnetic field $\tilde{\mathbf{B}}$, i.e., $\varepsilon_{\parallel} = \langle (\tilde{\mathbf{v}} \times \tilde{\mathbf{B}}) \cdot \mathbf{b}_{\mathrm{n=0}} \rangle$, where $\langle \cdots \rangle$ denotes magnetic flux surface average. Toroidally, the dynamo emf generates a negative loop voltage on the order of mV/m in the core ($\rho_p < 0.2$), which is equivalent to increased current diffusion. Outside the plasma core ($0.2 < \rho_p < 0.4$), the toroidal dynamo loop voltage is positive, thereby reducing the current diffusion rate. The reverse distribution of dynamo loop voltage continuously redistributes the plasma current and magnetic flux from the core region outward. As a result, the current density profile remains flat across a wide radius ($\rho_p < 0.4$), and q_0 stays close to unity.

Besides, excellent cancellations are identified between the negative dynamo term and the positive non-inductive current drive in the toroidal induction equation of poloidal flux (ψ) and the toroidal current diffusion equation. Therefore, poloidal flux and current density profiles remain quasi-stationary due to flux pumping. Analysis of the toroidal magnetic field evolution also proves the conservation of toroidal magnetic flux (ψ_t). The conservation of toroidal and poloidal magnetic fluxes clamps q_0 around unity and prevents the destabilization of sawteeth.

The present simulation work marks an important milestone in successfully modeling the full-cycle flux pumping in the experimental hybrid scenario, using fully realistic plasma parameters. For the first time, it achieves a quantitative agreement with AUG experimental observations in terms of current redistribution and dynamo loop voltage. In parallel, parameter scans of the current source, viscosity, resistivity, etc., and extended MHD developments are being carried out. These efforts are critical for understanding the flux pumping mechanism through direct 3D MHD simulations and for calibrating a fast surrogate model being developed by colleagues. The fast surrogate model aims to efficiently predict the amplitude of dynamo loop voltage and assess the feasibility of flux pumping in existing tokamaks like AUG [3] and JET, and future larger devices like ITER and DEMO, which is of great significance to the scenario design of tokamak fusion reactor.

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