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Magnetic flux pumping in the hybrid tokamak scenario: Nonlinear MHD simulations and ASDEX Upgrade discharges

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The hybrid tokamak scenario is characterized by low magnetic shear in the plasma core and a central value of the safety factor close to unity. It represents a hybrid between standard scenarios and advanced scenarios [1] and is a candidate scenario for ITER [2] and DEMO [3]. The hybrid scenario allows for high-performance, sawtooth-free operation with extended discharge lengths and has the advantage that its characteristic safety factor profile is automatically maintained. The latter property of hybrid discharges is due to a self-regulating current redistribution mechanism called magnetic flux pumping [4] which had not been understood yet. Current diffusion calculations that have been performed for hybrid discharges (e.g. [4,5] and the discharges described here) falsely predict values of the central safety factor below unity and hence sawtoothing. Understanding this effect is crucial in order to extrapolate the accessibility and properties of the scenario to future tokamaks.

Based on 3D nonlinear MHD simulations of tokamak plasmas, we propose an explanation for magnetic flux pumping [6,7]. In these simulations, a saturated quasi-interchange instability creates helical (m=1,n=1) perturbations of the magnetic and velocity fields in the central region of the plasma. Figure 1a) shows the perturbation of the poloidal velocity stream function (red: positive, blue: negative) in a quarter of the torus for such a simulation. The perturbations combine via an MHD dynamo to give an effective loop voltage flattening the background current density profile in the plasma core. This mechanism is self-regulating and prevents sawtoothing by keeping the central safety factor profile flat and close to unity. Figure 1b) compares the safety factor profiles in a 2D simulation (transport only) and a 3D simulation (where the dynamo loop voltage effect occurs) of the same set up. Since the quasi-interchange instability is pressure-driven, the maximal amount of flux pumping that can be provided by the dynamo loop voltage effect scales with the pressure. The beta threshold for the avoidance of sawteeth depends on how much the current density is being peaked centrally, e.g. by central current drive.

In ASDEX Upgrade tokamak discharges which have been set up to test this model, measurement results qualitatively agree with these predictions as can be seen in figure 1c). In these discharges, positive ECCD has been applied in several steps to drive q_0 to lower values, while at the same time an NBI power scan has been performed to increase beta, resulting in an alternation between sawtoothing and sawtooth-free phases. During the sawtooth-free phases, experimental evidence for anomalous current redistribution, leading to $q \approx 1$ in the core, is found in accordance with the theoretical model. An (m=1,n=1) mode is observed between sawteeth and continuously during the sawtooth-free phases. A quantitative comparison between theory and experiment by means of nonlinear MHD simulations based on these ASDEX Upgrade discharges is ongoing work.

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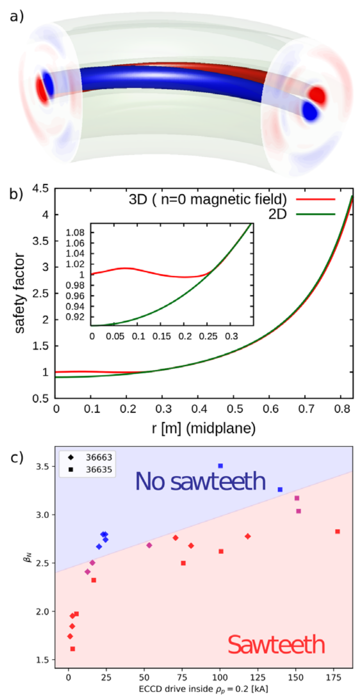

Figure 1.