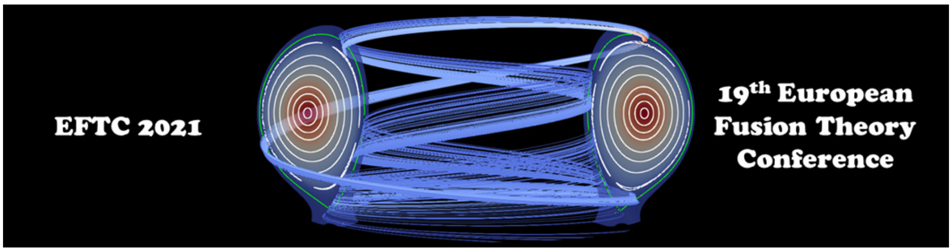

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Magnetic flux pumping in the hybrid tokamak scenario: Theory, simulations and experimental validation

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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 and is a candidate scenario for ITER and DEMO. 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 which had not been understood yet. Current diffusion calculations that have been performed for hybrid discharges 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 performed with the M3D-C1 code, we propose an explanation for magnetic flux pumping. 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. 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. 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 theoretical predictions. In these discharges, positive ECCD has been applied in several steps to drive the safety factor on axis 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 by a continuous (m=1,n=1) mode, leading to $q \approx 1$ in the core, is found in accordance with the theoretical model. A quantitative comparison between theory and experiment is ongoing work. To this end, nonlinear MHD simulations using the new full MHD model of the JOREK code have been set up based on selected time points during the different phases of one of the described ASDEX Upgrade discharges.

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