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[REGULAR POSTER TWIN] Experimental Evidence of Magnetic Flux Pumping at ASDEX Upgrade

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High performance advanced tokamak scenarios are very attractive for future burning plasmas. They can be achieved by elevating the central q-profile to values around unity to stabilize the sawtooth instability, which would otherwise reduce performance and could trigger deleterious instabilities. High-β plasmas can develop such a flat elevated central q-profile in the presence of MHD modes that modify the current profile [1]. The self-regulating mechanisms leading to this anomalous evolution of magnetic flux can be referred to by the general term "magnetic flux pumping". At DIII-D, flux pumping was observed in the presence of a 3/2 tearing mode, as well as when inducing a helical core via external perturbation coils [2]. In the work presented here, experimental evidence of anomalous current redistribution due to the dynamo effect produced by a 1/1 quasi-interchange instability [3] is discussed. It is shown that the ability of the mode to redistribute the centrally driven current, and thereby to suppress sawteeth, scales with the plasma pressure. This is potentially important for future non-inductive tokamaks, as it could provide a way to redistribute the current driven by electron cyclotron current drive (ECCD), which drives current most efficiently in the plasma centre. The flux pumping mechanism would redistribute current outward, maintaining a flat central q-profile around unity and maximizing both current drive efficiency and plasma stability at high β_N.

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A theoretical model based on recent simulations suggests that flux pumping can occur in the presence of a saturated ($_0$, β_N) interchange-like mode [4]. The flow in the convection cell combines with the perturbation of the magnetic field via the dynamo effect to generate an effective negative loop voltage in the plasma core. This prevents the central current density from peaking and thereby flattens the core $m = 1$-profile. The mechanism is self-regulating such that the core q-profile is clamped to values close to unity. Figure 1a shows the central electric field resulting from a 1/1 mode predicted by simulations, plotted against the central loop voltage necessary to keep q$n = 1$ around unity. The latter depends on internal and external parameters that lead to central current peaking, like externally induced current drive. In the cases that lie above the line, the magnetic flux pumping mechanism is sufficiently strong to prevent sawtoothing, whereas in the cases below the line, q is below unity and sawtoothing occurs. The simulation results suggest that the strength of the flux pumping mechanism depends on the core pressure. This dependency on $_0$ stems from the pressure-driven nature of the 1/1 quasi-interchange mode. The simulations shown here use a generic tokamak geometry, but simulations based on ASDEX Upgrade (AUG) discharges are underway. The experimental results shown in figure 1b support the theoretical model and will be discussed below.

With the combination of the imaging motional Stark effect diagnostic (IMSE) [5] at AUG and the IDE equilibrium solver [6,7], changes of q_0 as small as 0.1 are measurable, even in the plasma center. Together with the current drive capabilities of the upgraded electron cyclotron resonance heating (ECRH) systems [8], AUG constitutes the ideal device to perform experiments that test these simulations. In discharges featuring a 1/1 mode, positive ECCD current was applied in several steps to decrease β_N and trigger sawteeth. At the same time, an NBI power scan was performed to increase the q value over the threshold necessary for the mode to suppress sawteeth at a given central current drive.

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Figure 2 shows the heating power, q_0, ECCD, 1/1 mode activity and β_N in an AUG discharge with 800kA plasma current, a β_N of 5.2 and an q_0 factor of 1.1. Five phases are discussed in the following. The red shading indicates the presence of sawteeth, the blue shading their absence. The first phase starts with large sawteeth. After β_Ns, the measured central q_0 profile remains flat and clamped around unity. The last large sawtooth is observed around 1.62s, but small sawteeth still remain. At 1.65s, 1/1 mode activity first appears. Once q_{95} is increased above 2.4 the small sawteeth disappear as well, even when the central ECCD is increased. When the ECCD is increased further, above 130kA, sporadic small sawteeth reappear and become more frequent with more ECCD. In the last phase, the driven current is reduced and the sawteeth disappear again.

The bottom panel shows the modelled H_{98} in red, resulting from an equilibrium reconstruction which takes external magnetic measurements, kinetic profiles, current diffusion and a sawtooth current redistribution model into account [7]. The blue curve shows the estimated $t = 1.55$ when additionally taking into account the local measurements from the IMSE diagnostic, which will be referred to as "measured q". It can be seen that in phase III, without sawteeth, β_N should drop well below unity if no other current redistribution mechanism were present besides neo-classical current diffusion. The modelled and measured q_0 profiles for this phase are shown in the right panel. The measurements show that the central safety factor stays stable around one, suggesting an anomalous modification of the current profile. At the beginning of phase IV, the modelled q_0 is sporadically increased to unity by sawteeth, but drops well below 1 between the sawteeth. Since such a low q_0 would immediately trigger a sawooth, this suggests that the flux pumping mechanism still plays a role, but is not strong enough to completely suppress the sawteeth. This can also be seen in the measured q_0, which remains closer to 1.

The measured q and ECCD current from the different phases in this experiment are plotted in figure 1b (diamonds). The circles show the results from a similar discharge with more heating power, resulting in a higher q_0. For a comparison with the theoretical predictions (figure 1a), here q_0 is used as a proxy for the electric field that can be created by the 1/1 mode and the central ECCD current as a proxy for the electric field necessary to keep the central q_0 around unity. At a given ECCD current, β_N needs to exceed a certain threshold to enter the sawtooth free regime. At a higher ECCD current, this threshold increases. This supports the simulation results from reference [4] where the flux pumping mechanism in the simulations is only able to prevent sawtoothing at sufficiently high β_N, and where the threshold is dependent on central current drive peaking.

In the proposed contribution, results from simulations based on the experimental data from AUG discharges will be presented. The qualitative and quantitative agreement with the electric field deficit in the experiment, calculated from the difference between the modelled and measured toroidal current, will be discussed.

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