FLUX PUMPING IN ASDEX UPGRADE, JET AND JOREK

[1]A. BOCK, [1]A. BURCKHART, [2]G. PUCELLA, [3,4]F. AURIEMMA, [5]E. AYMERICH, [6]C. CHALLIS, [2]E. GIOVANOZZI, [6]N. HAWKES, [6]M. PORADZINSKI, [1]H. ZHANG, [1]R. FISCHER, [6]D. KING, [6]D. KEELING, [1]R. SCHRAMM, [1]V. IGOCHINE, [4]C. PIRON, [1]J. STOBER, [1]T. PÜTTERICH, [1]J. HOBIRK, [6]P. JACQUET, [1]M. HOELZL, [7]E. JOFFRIN, [4]M. BARUZZO, [7]R. DUMONT, [1]S. GÜNTER, [1]H. ZOHM, [8]JET CONTRIBUTORS, the [9]WPTE TEAM, and the [10]ASDEX UPGRADE TEAM

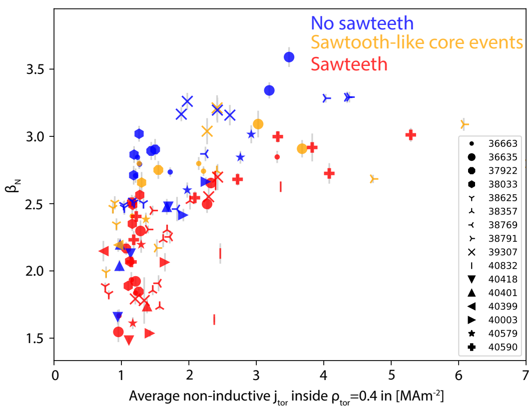
[1]Max-Planck-Institut für Plasmaphysik, Garching bei München, Germany
[2]ENEA, Frascati, Italy
[3]ISTP, CNR, Padova, Italy
[4]Consorzio RFX, Padova, Italy
[5]UNICA, Cagliari, Italy
[6]CCFE, Abingdon, United Kingdom
[7]CEA, Saint-Paul-lez-Durance, France
[8]see author list of J. Mailloux et al. 2022 Nucl. Fusion
[9]see author list of E. Joffrin et al. 2024 Nucl. Fusion
[10]see author list of H. Zohm et al. 2024 Nucl. Fusion

Email: alexander.bock@ipp.mpg.de

This contribution presents results of experimental investigations of the flux pumping phenomenon in the ASDEX Upgrade (AUG) and JET tokamaks as well as the first quantitatively consistent simulations using the JOREK code.

Flux pumping has not only been comprehensively characterised in the AUG tokamak, but dedicated experiments in the JET tokamak also allow us to report evidence of the phenomenon in a larger device for the first time. Also, first non-linear 3D simulations with realistic parameters using the magneto-hydrodynamics (MHD) code JOREK will be presented, showing quantitative agreement with experimental observations.

Anomalous flux redistribution ("flux pumping") is a self-regulating MHD phenomenon. This presentation focuses on flux pumping induced by the dynamo effect of a continuous, saturated quasi-interchange mode (m,n=1,1) located near the axis of a tokamak plasma [1]. It clamps the central safety factor q to unity, thereby maintaining an as peaked as possible toroidal current density profile just short of being unstable to sawtooth crashes. In doing so, it avoids sawteeth by means of self-organisation without complex plasma current control schemes. A more peaked current profile is known to enhance ideal MHD stability while the prevention of sawtooth crashes helps to avoid triggering resistive MHD modes. Together, this could be of considerable benefit for future tokamak fusion power plants (FPPs) as it allows them to operate reliably at low q_{95} and thus high confinement, i.e. at high plasma pressure. Moreover, the continuous redistribution of flux is linked to an effective redistribution of current away from the axis, thereby allowing the deposition of external electron-cyclotron current drive on-axis where it is most effective, before it is then pumped off-axis where it supports the current profile. This increases the efficiency of external current drive.



In order to design future FPPs that make use of flux pumping, robust predictive models that allow extrapolation must be developed. To this end, comprehensive investigations of flux pumping have been performed both in experiment and simulation to determine the conditions under which flux pumping can occur. Of particular interest are both the drive of the mode inducing the dynamo effect as well as the strength of the resulting effect. Further parameters such as the magnetic geometry or machine size may also play a role.

In AUG, a robust flux pumping scenario has been developed and probed extensively to determine the existence space of flux pumping [2]. In this scenario, flux pumping can be diagnosed by observing the continuous 1,1-mode in the absence of sawtooth crashes as well as a q-profile clamped to 1 near the axis (determined with internal magnetic measurements such as MSE or polarimetry) while conventional modelling would predict a continued drop of q_0 below unity. The mode is thought to be driven by β or its gradient. Thus, to increase the drive, the plasma pressure is increased via neutral beam heating. This ultimately allows the mode to redistribute sufficient flux to clamp the central safety factor. The mechanism is self-regulating, i.e., increased redistribution would further push q above 1, thereby weakening the mode again. Overall, the result of increasing plasma pressure is sawtooth crashes becoming less frequent as inward current diffusion is counteracted until the crashes disappear entirely despite conventional modelling with flux/current diffusion suggesting a continued potential for reconnection events. Scanning the plasma pressure allows for a quantitative assessment of the needed drive for flux pumping. In order to quantify the strength of the redistribution, electron-cyclotron co-current drive (ECCD) is added on-axis, which requires the mode to redistribute additional flux to clamp q at 1 – the point where sawteeth re-appear gives a quantitative indication that the redistributive ability of the mode has been overwhelmed. In figure 1, the outcome of such scans is summarised, matching the expectations from theory: flux pumping sets in above a threshold β_N (~2.5) and increases in strength with β, allowing for more redistribution at even higher pressures. This contribution will expand on these phase space investigations to also include the dependence on other parameters such as q_{95}.

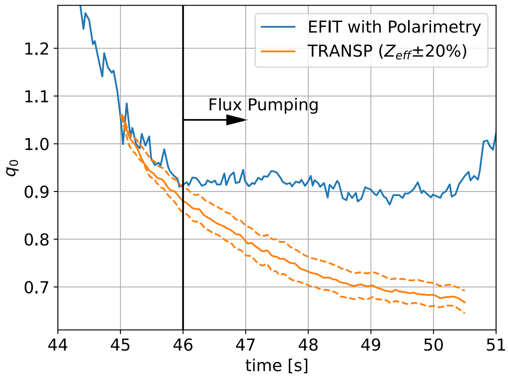


Figure 2: Comparison between q_0 from TRANSP modelling and EFIT with polarimetry for JPN103110.

Future FPPs will dwarf any present devices which makes the device size an important parameter whose effect must be understood to derive robust models. To this end, dedicated flux pumping experiments have been conducted in the JET tokamak for the first time. The major difference to the investigations in AUG is the lack of ECCD and thus no possibility to scan the mode strength. Moreover, JET's size and heating systems scale disproportionally with respect to AUG, allowing only marginal access to plasma pressures high enough to allow for flux pumping. Nevertheless, a JET flux pumping scenario was successfully developed based on the established hybrid scenario approach and will be presented here. For this, a current overshoot technique is used to induce a wide, flat q-profile in the plasma centre optimal for a central 1,1-mode. The plasma is then heated to reach β_N of about 2.5, similar to AUG, exhibiting a lack of on-axis sawtooth crashes. Comparison between EFIT equilibria and conventional current diffusion calculated by TRANSP reveals a discrepancy that suggests that anomalous flux redistribution is occurring (cf. figure 2).

State of the art MHD models such as JOREK are expected to be able to reproduce the flux pumping phenomenon in simulation. This is needed to develop a robust understanding of the physics behind it such that authoritative extrapolations from present experiments to future FPPs are possible. For the first time, realistic parameters from an AUG flux pumping pulse have been used to drive non-linear 3D calculations in JOREK, with which it was possible to quantitively reproduce the experimental observations (see figure 3.). This contribution will give an introduction to these results, while a comprehensive and detailed discussion of the JOREK simulations has also been submitted as a separate synopsis [3].

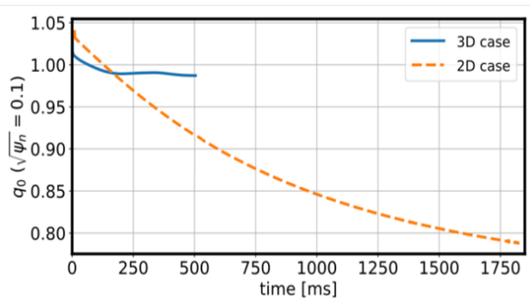


Figure 3: Only 3D treatment with JOREK allows capturing the dynamo-induced clamping effect as calculated for AUG#36663 [3].

REFERENCES

[1] S.C. Jardin *et al* 2015 *Phys. Rev. Lett.* **115** 215001
[2] A. Burckhart *et al* 2023 *Nucl. Fusion* **63** 126056
[3] H. Zhang, *Progress on nonlinear MHD modelling of flux pumping and hybrid scenario for AUG plasmas*