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MAGNETIC FLUX PUMPING IN ASDEX UPGRADE, JET AND JOREK

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

[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]SUNICA, Cagliari, Italy
[6]UKAEA, Culham Campus, 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

Abstract

This contribution presents experimental investigations of the magnetic flux pumping phenomenon in the ASDEX Upgrade (AUG) and JET tokamaks, alongside on overview over the first quantitatively consistent simulations using the JOREK code. Flux pumping is a self-regulating magneto-hydrodynamic (MHD) phenomenon, induced by the dynamo effect of a continuous, saturated $(m, n = 1, 1)$ quasi-interchange mode, which clamps the central safety factor, q, to unity. This self-organization mechanism prevents sawtooth crashes without external control, which is of considerable benefit for future fusion power plants (FPPs) as it may allow for reliable operation at high plasma pressure and confinement. The phenomenon has been comprehensively characterized in AUG, and this work reports the first evidence of flux pumping in the larger JET tokamak, demonstrating its scalability. Furthermore, first non-linear 3D MHD simulations with JOREK, using realistic parameters, are presented and show quantitative agreement with experimental observations, which is a crucial step towards developing predictive models for FPPs.

1. INTRODUCTION

The anomalous redistribution of poloidal magnetic flux, or magnetic flux pumping (FP), is a magneto-hydrodynamic (MHD) phenomenon observed in tokamak fusion experiments and of significant interest for future fusion power plants. In tokamak plasmas with sufficiently high current, the safety factor, q, which quantifies the helicity of the magnetic field lines, can drop below unity in the core. This condition makes the plasma susceptible to magnetic reconnection events, the most common of which is the sawtooth instability.

During a sawtooth crash, a sudden reconnection event occurs within the $q = 1$ flux surface. This leads to a momentary loss of confinement in the deep core of the plasma, redistributing the current density and flattening the core temperature and density profiles. The resulting drop in central plasma pressure is detrimental to core confinement. Moreover, the outward-travelling pressure wave can trigger secondary instabilities, such as neoclassical tearing modes (NTMs), further degrading plasma performance. The conventional sawtooth cycle is initiated by a (1,1) kink mode precursor, which displaces the flux surfaces. Where these surfaces are brought close together, steep gradients form and reconnection can set in, allowing particles to flow from hotter, denser inner surfaces to outer ones.

However, under certain conditions, particularly when the central q-profile is very flat near unity and the plasma pressure is sufficiently high, a different phenomenon can emerge. Instead of a disruptive sawtooth crash, a persistent, saturated (1,1) quasi-interchange mode can develop [1, 2, 3]. This mode establishes a macroscopic plasma flow pattern that, together with associated magnetic field perturbations, produces a dynamo effect ($\vec{E} = \vec{v} \times \vec{B}$). This dynamo reduces the loop voltage centrally while raising it off-axis, which causes a reduction of the central toroidal current density while increasing it off-axis (cf. sec. 4). The net effect is that the q-profile is naturally clamped around $q = 1$, preventing it from dropping further and thereby robustly stabilizing sawtooth crashes. This process is self-regulating as a further increase of q_0 weakens the necessary flow-patterns, thereby reducing the dynamo effect again.

This natural stabilization mechanism is highly desirable, as it may obviate the need for external methods of sawtooth control, such as auxiliary current drive. While this process is not without cost – it requires a sufficiently high core plasma normalized pressure β and may involve some confinement trade-offs – the benefit of avoiding sawtooth crashes and their secondary effects could be substantial for a fusion reactor. This phenomenon has been previously identified in several devices, including ASDEX Upgrade (AUG) [4], EAST [6], and DIII-D [7, 8], and it is also being reported at this conference for MAST-U [9]. This paper builds upon that foundation, presenting new experimental results from AUG and the larger JET tokamak, as well as significant progress in first-principles modeling with the JOREK code [10].

2. FLUX PUMPING IN ASDEX UPGRADE

Systematic investigations of the flux pumping regime have been carried out on the ASDEX Upgrade tokamak on the basis of theoretical work presented in [2, 3]. There it is shown how at sufficiently high β, the impact of the 1,1-mode is sufficient to avoid sawtooth crashes, thereby dividing the parameter space into an area with and without such crashes.

The experiments at AUG have explored this parameter space in which flux pumping occurs by performing comprehensive scans of β on the one hand, and on the other hand auxiliary current drive in the plasma centre up to and beyond the point of overwhelming the mode to identify the conditions required for its access and sustainment.

Figure 1 (left) shows key parameters of a typical flux pumping experiment in AUG. β is increased using additional neutral beam heating, which allows transitioning from phase I with sawteeth into phase II without. Then, additional electron-cyclotron current drive (ECCD) is applied in the plasma centre (cf. sub-plot (a)), which adds additional current that the mode has to redistribute to continue avoiding sawteeth. As more ECCD is applied, a transition into phase III occurs, where sawteeth happen again – the mode is no longer able to redistribute all current. Finally, returning to the initial level of ECCD allows returning back to a pure flux pumping state. Throughout this time, the 1,1-mode is clearly visible in a spectrogram of the magnetic data (sub-plot (c)).

The disappearance of sawteeth by itself is not a definitive indication for anomalous redistribution of magnetic flux. It is possible, for instance, that changes in the resistivity profile merely prevent $q < 1$ from occurring, and thus also any sawtooth crashes. Instead, the clearest evidence for anomalous behaviour is when conventional flux diffusion models are contradicted by actual measurements of the magnetic equilibrium in the plasma centre. This is shown in sub-plot (d): in the phases without sawteeth, a conventional flux diffusion model [11] predicts that q_0 should continue to drop to values far below unity. In contrast, reconstruction of q_0 using the high-accuracy imaging motional Stark effect (IMSE) diagnostic [12] show a continued clamping of q_0 to unity, suggesting anomalous redistribution of current and flux. For two example times the corresponding full radius q-profiles are shown in sub-plots (e) and (f), clearly showing the discrepancy between model and measurement when no sawteeth occur, and the match when they do take place.

This trajectory through the parameter space is summarised on the left of fig. 2. There, an idealised sketch of the example shown in fig. 1 is given. The right graph summarises many such scans performed over the last campaigns in AUG using β_{N} as a proxy for the free energy driving the mode and ECCD inside the approximate extent of the 1,1-mode as the amount of redistribution needing to occur. Generally, the theoretical predictions are confirmed: at high β and low ECCD, sawteeth disappear while they remain at lower β with more ECCD. Nevertheless, a scatter in the data remains, which points to further, so far unaccounted parameters which are still under investigation.

Overall, the results confirm that flux pumping is a robust phenomenon in medium-sized devices and provide a rich dataset for model validation. An illustration of the typical signature of the flux pumping state in AUG is given, highlighting the clamping of the central q-profile and the persistent (1,1) mode structure, with more information being available in [4].

Recent experiments that focus on marginal cases (lower β / temperature peaking) suggest a close relationship between the FP regime and similar-behaving ones dominated by fishbone activity like [5]. In the shots listed in fig. 2(b), all examples exhibit the continuous mode, but in some it is accompanied by fishbone activity of similar frequency. This is also visible in fig. 1(c), especially phases I and III. In the most recent experiments, fishbones can persist even after the central q-profile has continued to drop such that the 1,1-mode has become unviable. It is still under investigation whether these processes are competing under these conditions, or merely complementary.

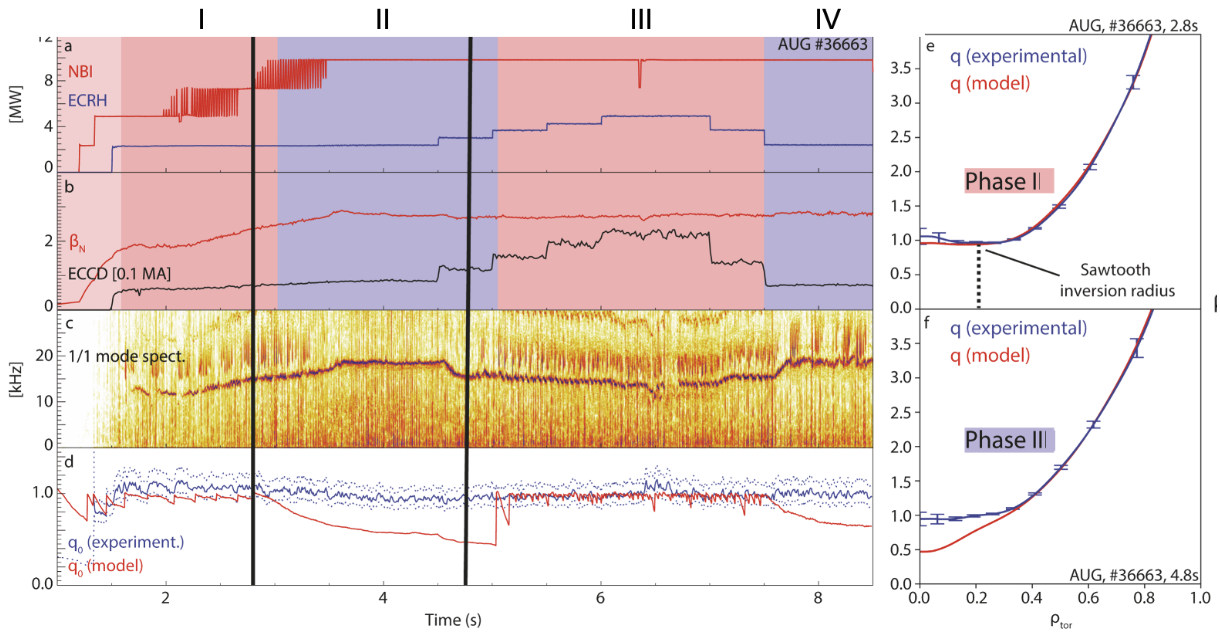
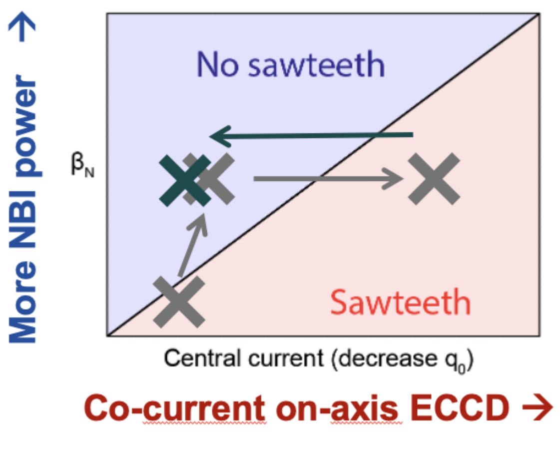
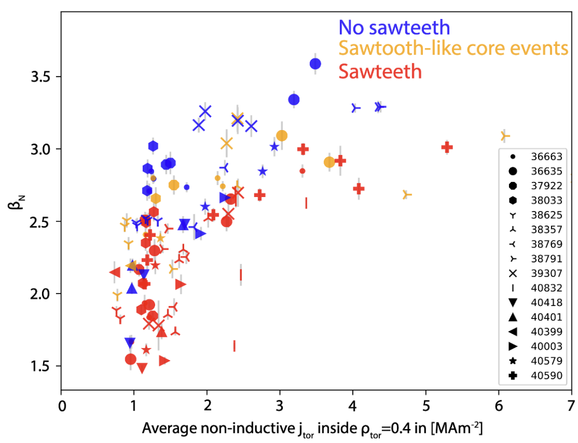


FIG. 1. (a) Neutral beam heating and electron-cyclotron resonance heating power. (b) Normalised plasma pressure β_{N} and centrally driven electron-cyclotron current. (c) Magnetic pickup coil Fourier spectrogram. (d) q_0 as determined through equlibrium reconstruction with internal constraints from the IMSE diagnostic in blue compared with modelled q_0 using conventional flux/current diffusion. (e+f) Reconstructed and modelled q-profiles for a flux-pumping and non-flux-pumping phase, respectively.
In the blue-shaded phases (II+IV), modelled and reconstructed q are in contradiction, suggesting an anomalous redistribution of poloidal flux or toroidal current density is occurring. Excessive current drive in phase III overwhelms the redistributive ability and triggers sawtooth crashes. Reproduced from [4].



(a) Sketch of the phase diagram. Crosses and arrows represent approximate trajectory through phase space shown in figure 1.



(b) Experimental phase diagram. Broad agreement with the expected phase space exists but a scatter remains that points towards additional, so far unaccounted for parameters.

FIG. 2. Comparison of the sketched and experimental phase diagrams.

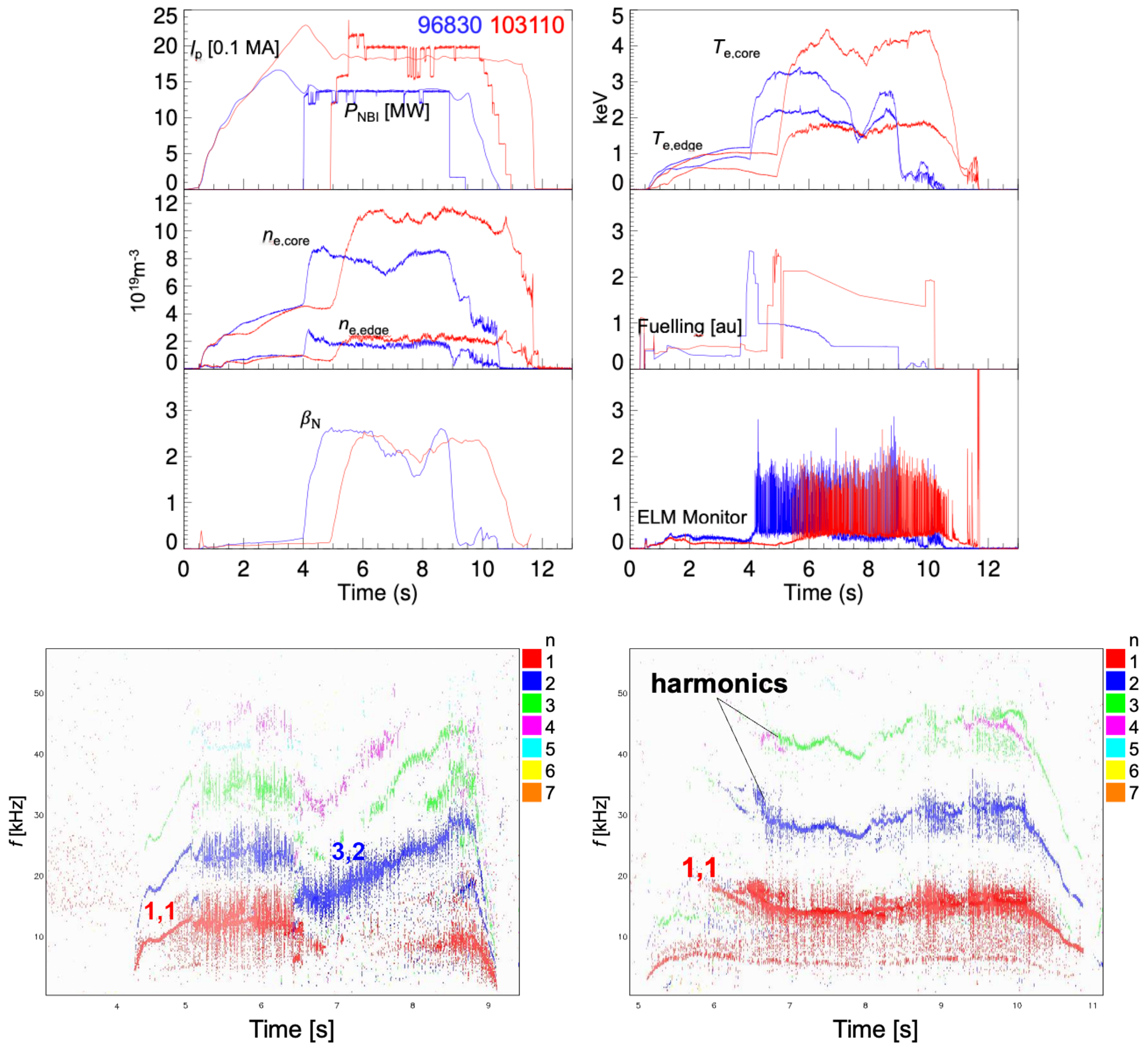


FIG. 3. Flux pumping in JET. Top: Key plasma parameters for JET pulses #96830 (blue) and #103110 (red). Bottom left: MHD spectrogram showing the persistent (1,1) mode in #96830 (red) until ca. 6.5 s when a (3,2) NTM (blue) is destabilised by a sawtooth crash. Bottom right: MHD spectrogram showing the persistent (1,1) mode in #103110 (red) and no other MHD.

3. FLUX PUMPING IN JET

A key question for the applicability of magnetic flux pumping to future power plants is its scalability to larger devices. To address this, dedicated experiments were conducted on the JET tokamak, which is approximately twice the linear size of AUG. Due to this alone, the resistive timescale will already be increased by a factor of 4 compared to AUG, requiring appropriately longer experimental phases. Furthermore, due to the absence of an EC system on JET, only scans in the vertical direction of the diagrams in fig. 2 were possible.

Although no explicit evidence for flux pumping on JET has been published in the past, hybrid scenario pulses with flat central q-profiles have been carried out in JET for many years [14, 15]. These scenarios are

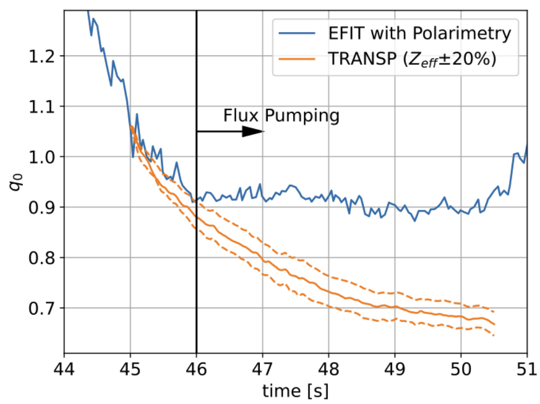


FIG. 4. Comparison between q_0 as determined by Polarimetry-constrained EFIT equlibria (blue) and q_0 modelled using conventional magnetic flux diffusion in the TRANSP code (orange), both for JET pulse #103110.

the most likely candidates for demonstrating flux pumping in JET, and so the obvious experimental approach was to begin with a promising JET hybrid shot. The chosen starting point was #96830, which exhibited both the flat central q-profile due to the use of the current-overshoot technique typically used on JET to achieve hybrid conditions, and supposedly high enough β_{N} above 2, resulting in a continuous 1,1-mode in the early phase of the shot. However, it also exhibited intermittent sawtooth crashes, the third of which ultimately triggered a secondary 3,2-NTM as shown in the lower left of fig. 3, deteriorating the confinement irrecoverably.

It should be noted that although β_{N} is being used as a proxy for the free energy available to drive the mode, it is not expected that a global quantity like β_{N} is actually the correct parameter for a first-principle-based approch to understanding the phenomenon. Instead, the plasma pressure (or its gradient) in the vicinity of the mode is probably more appropriate, albeit harder to determine experimentally. For this reason, the JET FP shots aimed at higher plasma current, which allows for absolutely higher confinement and thus pressure, including at the location of the mode.

Due to the unwanted NTMs occuring in the reference pulses, the experimental approach was to attempt to stabilise any NTMs by avoiding the occurrence of any sawtooth crashes in the first place. For this, ohmic pulses with varying plasma current and toroidal magnetic field were conducted to precisely determine the arrival time of $q = 1$. This was determined through ECE, which clearly showed when sawtooth precursors with mode numbers $m, n = 1, 1$ set in. Then, both heating and gas fuelling were adjusted accordingly to supply sufficient plasma pressure to ensure the continuous drive of the 1,1-mode rather than continued evolution into sudden reconnection by a sawtooth crash.

The optimisation process was accompanied by predictive modelling to determine the optimal timing for the actuators [13].

The key plasma parameters of reference pulse #96830 as well as of the first successful pulse exhibiting flux pumping (#103110) are shown on the top of figure 3. While the absolute pressure is higher in #103110 due to higher plasma current, the resulting β_{N} is the very close to the reference case (≈ 2.5).

As a result of the optimisation, JET pulse #103110 now exhibits a continuos 1,1-mode undisturbed by the otherwise occurring typical sawtooth crashes, and consequently also no NTMs. This is shown in the lower right graph of figure 3.

The most convincing evidence for flux pumping in JET comes from a direct comparison of the measured and modelled q-profiles. As shown in fig. 4, the safety factor profile obtained from polarimetry-constrained EFIT equilibria consistently shows a clamped profile with $q_0 \approx 1$. In contrast, transport modelling with the TRANSP code, which assumes classical neoclassical flux diffusion, predicts that the q-profile should continue to drop well below unity. This discrepancy is direct evidence of an anomalous, non-diffusive mechanism redistributing magnetic flux from the core to off-axis regions, consistent with the flux pumping dynamo.

Although no conventional sawtooth crashes were observed in #103110, there were signatures of reconnection events in general still occurring. Based on experience from AUG, where FP tends to set in at higher β_{N} than 2.5 (cf. 2(b)), it might not surprise that the results in JET seem marginal and full avoidance of sawtooth crashes does not occur. However, the observed events were not taking place on-axis as in a regular sawtooth crash, but off-axis. A comparison of such crashes and regular sawtooth crashes is shown in figure 5. Although the volume near the magnetic axis is not affected in these off-axis reconnection events, a drop in the

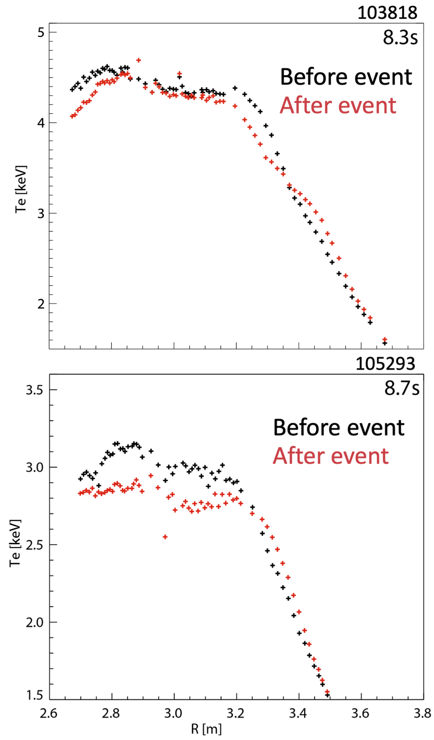


FIG. 5. Top box: example of an a-typical off-axis sawtooth crash observed in a JET FP pulse. Note the lack of change in the deep core, suggesting only off-axis reconnection. Bottom box: example of a typical sawtooth crash where the deep core is reduced due to on-axis reconnection, with a heat wave travelling outwards as a result.

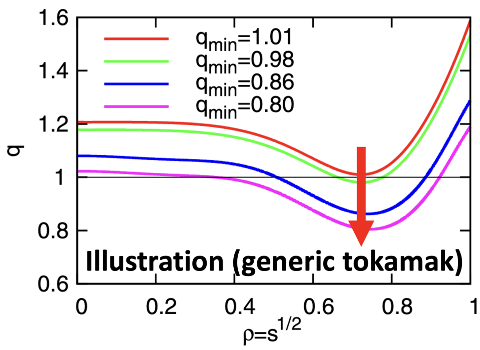


FIG. 6. Example of a q-profile dipping below unity off-axis while maintaining $q_0 \geq 1$. Reproduced from [16].

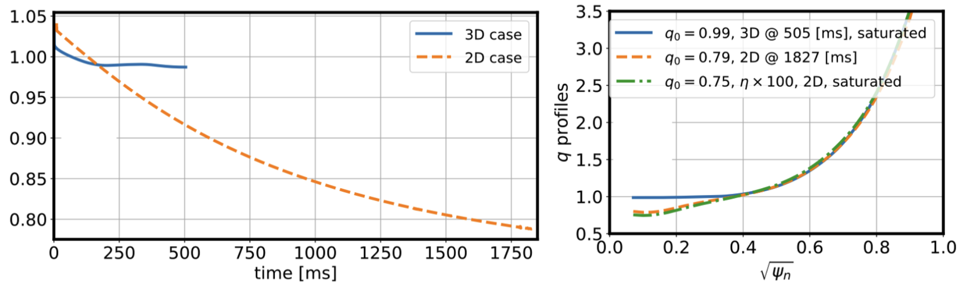


FIG. 7. Evolution of central safety factor (q_0) and q-profiles in 2D and 3D JOREK simulations (orange and blue, respectively), showing q-profile clamping only in the 3D case.

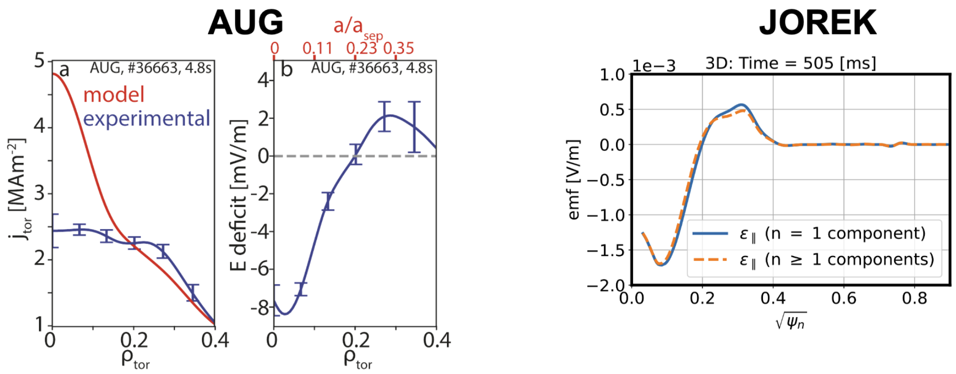


FIG. 8. Comparison of the E-field deficit from AUG experiments (left) and JOREK simulations (right), demonstrating qualitative and approximate quantitative agreement. Reproduced from [4] and [10].

temperature off-axis as well as an outward-travelling heat wave can be observed.

A plausible explanation for this observation would be the presence of a region of plasma in the vicinity of the axis that exhibits $q < 0$ while the very centre remains at or above unity (cf. fig. 6), thereby only allowing off-axis reconnection in the form of a double tearing mode. Ideally, this would be evidenced using high-fidelity equilibrium reconstruction using the MSE diagnostic. This was not possible throughout the shot because in order to achieve the necessary plasma pressure, most of JET's neutral beams were employed, which caused interference with the MSE system. Notching of the interfering beams was performed to allow for some MSE measurements, but these did not allow for sufficiently high accuracy in the reconstruction to confidently accept or reject the explanation.

As such double tearing modes could still trigger deleterious second-order instabilities due to the still outward-travelling heat wave emitted when reconnection takes place, it is necessary to further characterise the conditions under which this might happen and learn how to avoid it, if possible.

In summary, this experimental work documented, for the first time, evidence for anomalous flux redistribution in a larger tokamak in reactor-relevant conditions [17]. It demonstrates that flux pumping can exist in larger devices. Furthermore, the experiments provide a database for validation of physics models explaining flux pumping at larger major radius R.

4. SIMULATION WITH THE JOREK CODE

For a thorough physical understanding and predictive capability, experimental observations must be reproduced by state-of-the-art MHD simulations. So far, experiments have been guided by theoretical predictions in idealised geometry and without realistic plasma parameters, which has already yielded valuable results (see sections above). Recent work, however, using the non-linear 3D MHD code JOREK [18] has successfully simulated the flux pumping phenomenon for the first time in a quantitatively consistent manner. These simulations demonstrate that capturing this effect requires full 3D physics; equivalent 2D simulations show only conventional magnetic flux diffusion, similar to the TRANSP results.

In figure 7, the evolution and profiles of q as calculated by JOREK for phase II of the flux pumping shot described in section 2 are shown. The 3D simulation is cut short because of its high computational cost. Nevertheless, the expected behaviour can be seen: q_0 remains clamped to unity. This is also reflected in the q-profile shown on the right. In contrast, the case showing the evolution of q only considering 2D physics exhibits the same behaviour as conventional flux diffusion. Without 3D effects, the 3D structure of the (1,1)-mode cannot develop and no dynamo effect sets in. Conseuqnetly, the conventional behaviour results from this, essentially reproducing the results of simpler models such as TRANSP [19] or IDE [11].

It is of interest not only to match the experimentally observed behaviour qualitatively, but also quantitatively. A key point of comparison is the loop voltage deficit profile which represents the strength of the effect. Fig. 8 shows a comparison between the profile derived from AUG experiments on the left and that from JOREK on the right. The results show excellent qualitative agreement and an approximate quantitative match, confirming that the underlying dynamo physics is well-captured by the model. Qualitatively, the expected reduction in loop voltage in the very centre flanked by areas of increased loop voltage is reproduced. Since these JOREK simulations now use the actual parameters of the plasma, the results are also approximatively quantitatively matching the experiment within a factor of about 2-4. While these small quantitative differences remain, indicating areas for further refinement, this represents a major step forward in validating the understanding of flux pumping.

Recent simulations are presented in detail at this conference [20], including parameter scans to assess the parameter ranges within which flux pumping is effective.

5. SUMMARY AND FUTURE WORK

This paper has presented an overview of the magnetic flux pumping phenomenon, a self-organizing MHD mechanism that clamps the central q-profile at unity, thereby preventing sawtooth crashes. New experimental evidence from the JET tokamak demonstrates that this phenomenon is not limited to medium-sized devices and is scalable, which is a crucial finding for its potential application in future fusion reactors. Furthermore, for the first time, nonlinear 3D MHD simulations with the JOREK code have quantitatively reproduced experimental signatures of flux pumping, providing strong validation for the theoretical model of a dynamo driven by a (1,1) quasi-interchange mode.

Future work will proceed along several parallel paths. Experimentally, further investigations on ASDEX Upgrade will focus on the subtle access conditions for flux pumping, as small differences in the q-profile appear to be critical. This should also encompass studies with high populations of fast particles to understand potential interactions between flux pumping and fishbones.

Further experiments on tokamaks like MAST-U will also be pursued to explore the effects of different plasma shaping (aspect ratio, elongation). On the theory and simulation front, the computationally intensive JOREK simulations will be continued to further refine the models and also include effects of fast particles, for instance. A key goal is to use these validated, first-principles simulations to derive computationally cheaper, reduced models that can accurately predict the occurrence of flux pumping in future devices.

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