Progress on nonlinear MHD modeling of flux pumping and hybrid scenario for ASDEX Upgrade plasmas

H. Zhang[1,*], M. Hoelzl[1], I. Krebs[2,3], A. Burckhart[1], A. Bock[1], S. Guenter[1], V. Igochine[1], K. Lackner[1], R. Ramasamy[1], H. Zohm[1], JOREK team[4], and ASDEX Upgrade team[5]
[1] Max-Planck-Institut für Plasmaphysik, Garching, Germany; [2] Eindhoven University of Technology, Eindhoven, The Netherlands; [3] Dutch Institute for Fundamental Energy Research, Eindhoven, The Netherlands; [4] See author list of *M. Hoelzl et al 2024 Nucl. Fusion 64 112016*; [5] See author list of *H. Zohm et al 2024 Nucl. Fusion 64 112001*

*haowei.zhang@ipp.mpg.de

30th IAEA Fusion Energy Conference, Chengdu, China, 13–18 October 2025

ABSTRACT

Flux pumping was achieved in recent hybrid scenario experiments in the ASDEX Upgrade (AUG) tokamak [1]. The self-regulation mechanism of the AUG core plasma during flux pumping is investigated at realistic parameters with full magnetohydrodynamic (MHD) simulations using the JOREK code. A key milestone is achieved by quantitatively reproducing the clamped current density and safety factor profiles in the plasma core, demonstrating the effectiveness of the dynamo effect in sustaining the AUG flux pumping state. The dynamo term, of particular interest, is primarily generated by the pressure-gradient driven 1/1 quasi-interchange-like MHD instability. The work systematically extrapolates the parameter regimes of flux pumping from the above AUG base case by scanning dissipation coefficients and plasma beta. The simulation results reveal bifurcated plasma behaviour, including distinct states such as flux pumping, sawteeth, etc. The relationships between system dissipation, plasma beta, and different plasma states are carefully analyzed.

FEATURES OF FLUX PUMPING

- $q_0 \simeq 1$, shear-free in the core;
- m/n = 1/1 helical stationary plasma core;
- Dynamo prevents current & pressure from peaking;
- Sawtooth-free and self-regulating;
- Substantial share of non-inductive current;
- Hypothesis: higher current drive efficiency.

HYBRID SCENARIO AND AUG DISCHARGE #36663

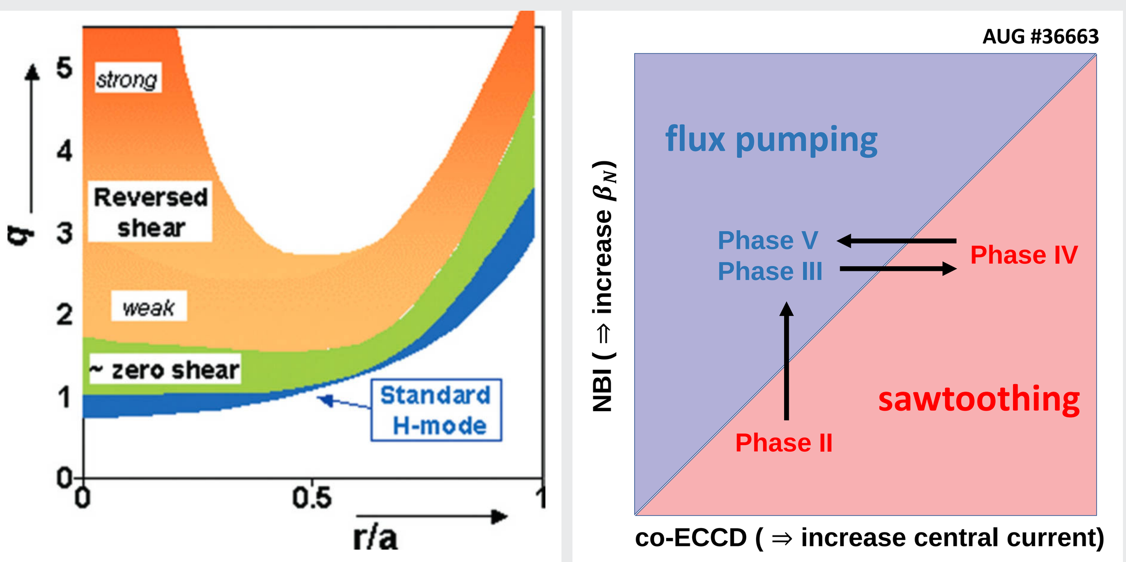

Figure 1: Left: q profiles for the ITER conventional scenario (blue), the hybrid scenario (green) and the reversed shear scenario (orange) [2]. Right: a schematic of AUG discharge #36663 [1].

RECONSTRUCTED AUG PROFILES

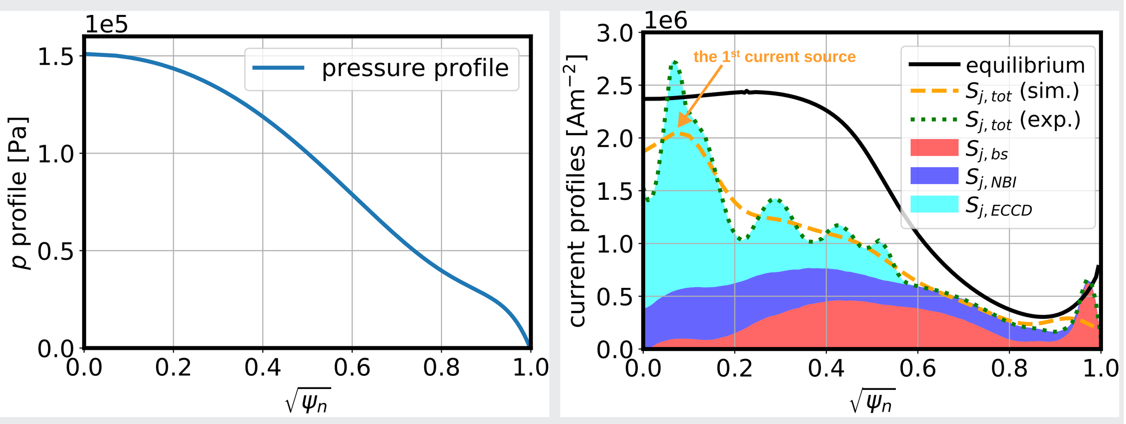

Figure 2: Initial profiles of pressure and current (source) for 3.75 ∼ 3.95 s of phase III.

PARAMETERS AND MHD MODEL

- **Normalized beta:** $\beta_N \simeq 3$;
- **Plasma current:** $I_p \simeq 0.806$ MA;
- **Spitzer resistivity:** $\eta_{\text{axis}} = 2.41 \times 10^{-9}\ \Omega \cdot \text{m}$;
- **Kinematic viscosity:** $\mu_{\text{axis}} = 2.70\ \text{m}^2 \cdot \text{s}^{-1}$;
- **Anisotropic heat conductivities:** $\kappa_\parallel/\kappa_\perp$ (electron) $\sim 10^{10}$;
- **Lundquist number:** $S \simeq 3 \times 10^9$;
- **Viscous Lundquist number:** $S_\mu \simeq 2 \times 10^6$;
- **Hartmann number:** $H \simeq \times 10^8$;
- **Magnetic Prandtl number:** $P \simeq 1400$;
- **Based on the single-fluid visco-resistive two-temperature full MHD model of JOREK.**

MHD DYNAMO IN TOROIDAL MAGNETIZED PLASMAS

- Dynamo theory has been adopted to study the self-regulating processes of toroidal magnetized plasmas, e.g., flux pumping in tokamak [3] and single-helical state in the reversed-field pinch (RFP) [4];
- MHD dynamo in Ohm's law for the mean field: $\langle \mathbf{E} \rangle \simeq -\mathbf{v}_0 \times \mathbf{B}_0 + \eta (\mathbf{J}_0 - \mathbf{S}_j) - \underbrace{\langle \delta\mathbf{v} \times \delta\mathbf{B} \rangle}_{\text{MHD dynamo}} + \underbrace{\langle \cdots \rangle}_{\text{Hall/diamagnetic dynamo [5]}}$;
- Balance between MHD dynamo and current drive during flux pumping [6]: $\partial_t \langle J_\varphi \rangle \approx \mu_0^{-1} \langle -\underbrace{\nabla^2 (\mathbf{v} \times \mathbf{B})_\varphi}_{\text{MHD dynamo}} + \underbrace{\nabla^2 [\eta (J_\varphi - S_j)]}_{\text{current drive}} \rangle$;
- M3D-C¹ modeling qualitatively reveals the role of the negative MHD dynamo in flux pumping and predicts a $\beta_{\text{threshold}}$ [7];
- Flux pumping (dynamo) has been studied for AUG [1, 6] (this work), EAST (diamagnetic dynamo) [8], DIII-D [9, 10], JET [11, 12], etc.

COMPARISONS: 2D VS 3D CASES

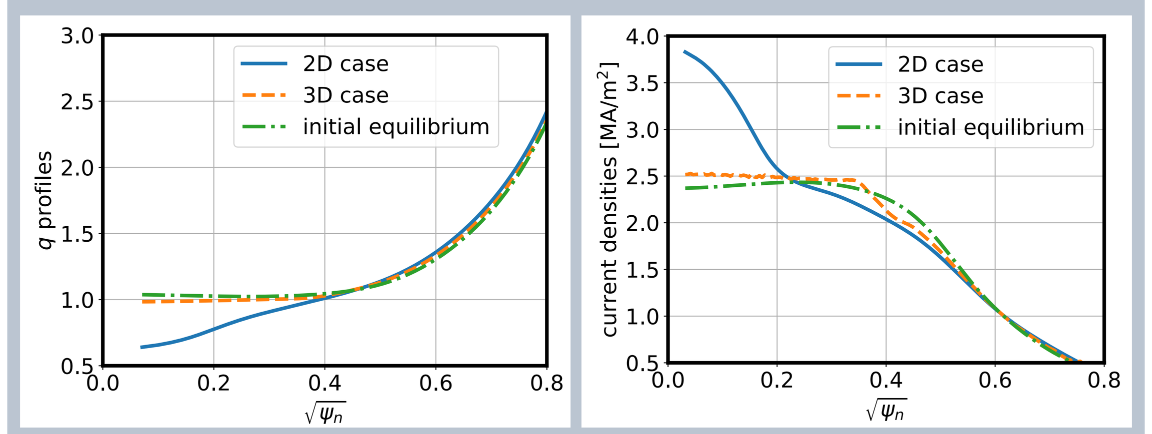

Figure 3: The q (left) and current density (right) profiles at the saturated stages of the 2D and 3D simulations, as well as of the initial equilibrium.

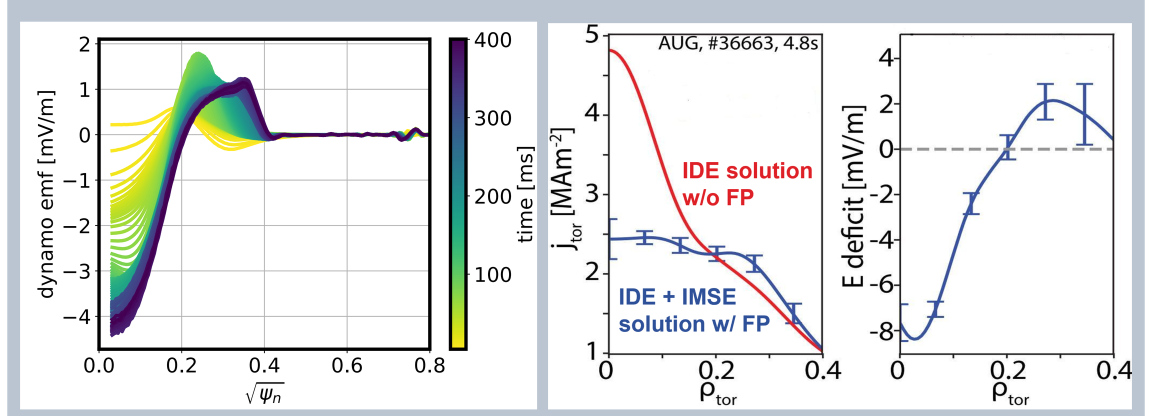

Figure 4: The dynamo electric field vs. time from the 3D simulation (left). Reconstructed profiles of the flux pumping phase at 4.8s of discharge #36663: (middle) experimental (blue, with IMSE data) and modeled (red, without IMSE data) current densities; (right) corresponding effective electric field deficit [1].

- In 2D simulation, $q_0 \simeq 0.6$; in 3D simulation, q_0 remains near unity ($\simeq 0.99$);
- The radial redistribution of toroidal plasma current is identified in the 3D simulation;
- The radial profiles of q and current density, along with the dynamo electric field, are quantitatively consistent with the AUG reconstructions.

PARAMETER REGIMES OF FP & ST

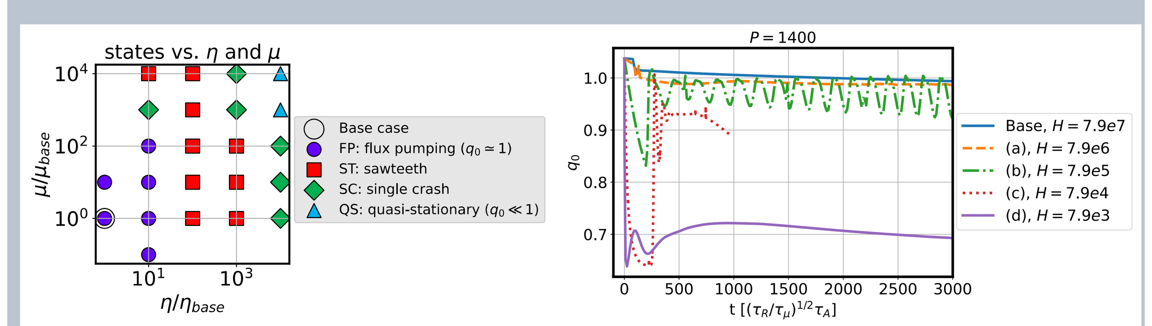

Figure 5: Left: different plasma states obtained at different system dissipations. Right: q_0 evolutions of four representative plasma states.

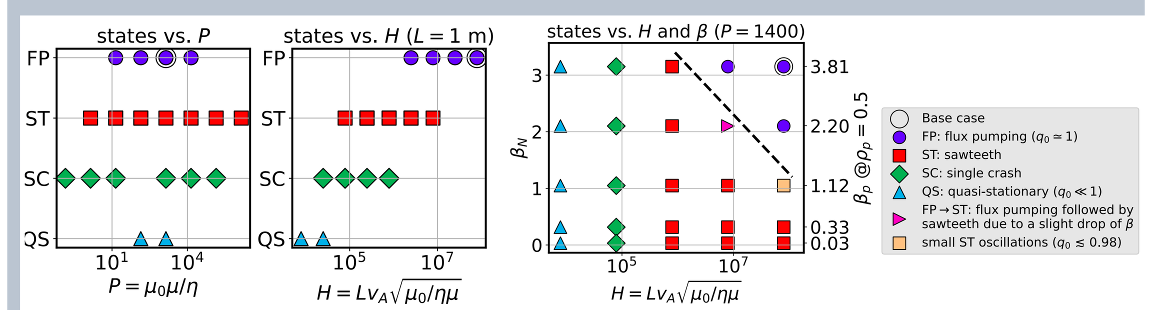

Figure 6: Plasma states plotted over (left) the magnetic Prandtl number and Hartmann number, and over (right) varying plasma beta and Hartmann number.

- Flux pumping exists at low dissipation regime (with High Hartmann numbers, $H \sim 10^7$);
- At lower Hartmann numbers, q_0 drops below unity, and states with sawteeth, single-crash state, and a stationary 1/1 island are obtained, respectively;
- There is a plasma beta threshold for accessing flux pimping.

DYNAMO EFFECT IN AUG CASES

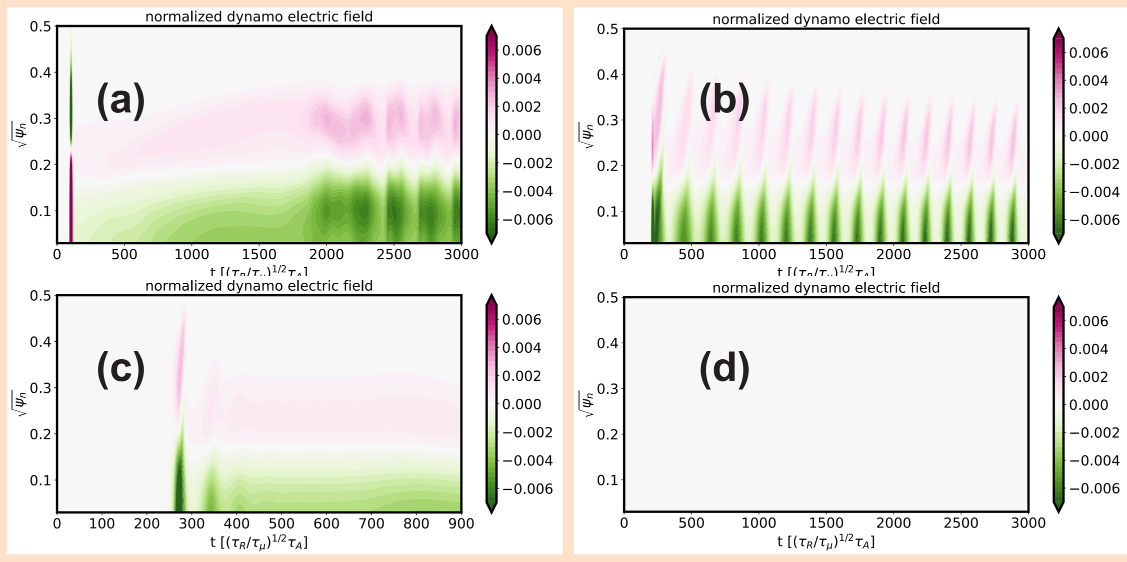

Figure 7: Temporal evolutions of the radial profile of dynamo electric field normalized by the increased ratio of resistivity, respectively for cases (a) $10 \times \eta_{\text{base}}$, (b) $10^2 \times \eta_{\text{base}}$, (c) $10^3 \times \eta_{\text{base}}$, and (d) $10^4 \times \eta_{\text{base}}$. P is fixed at 1400 for all cases.

- **(a) FP**: dynamo remains stable with the amplitude comparable to the current drive intensity ($q_0 \simeq 1.0$);
- **(b) ST**: dynamo exhibits periodic oscillations with the same period as that of the q_0;
- **(c) SC**: dynamo becomes stationary after the first sawtooth crash, the system enters a flux pumping like state ($q_0 \simeq 0.9$);
- **(d) QS**: dynamo fails to modulate q profile as its amplitude decreases to noise level ($q_0 \simeq 0.7$).

CONCLUSION AND OUTLOOK

[Conclusion]
- AUG flux pumping is reproduced with JOREK modeling [6];
- Negative MHD dynamo loop voltage is of the order of mV/m;
- 1/1 mode induced MHD dynamo clamps $q_0 \simeq 1$ and prevents current & pressure from peaking, thereby avoiding sawtooth onset;
- Parameter scans reveal the potential operating regimes of flux pumping: low system dissipation and high plasma beta;

[Outlook]
- Investigate the operating window of current source;
- Extended MHD model: two-fluid effect, finite Larmor radius (FLR) effect, energetic particles, fishbones;
- Modeling for the JET flux pumping experiments [12];
- Facilitate the development of a surrogate model [13].

REFERENCES

[1] A. Burckhart et al. *Nucl. Fusion* 63.12 (2023), 126056.
[2] A. C. C. Sips et al. *Plasma Phys. Controlled Fusion* 47.5A (2005), A19.
[3] S. C. Jardin et al. *Phys. Rev. Lett.* 115 (2015), 215001.
[4] D. Bonfiglio et al. *Phys. Rev. Lett.* 94 (2005), 145001.
[5] H. Ji et al. *arXiv preprint astro-ph/0110352* (2001).
[6] H. Zhang et al. *Nucl. Fusion* 65.6 (2025), 066001.
[7] I. Krebs et al. *Phys. Plasmas* 24.10 (2017), 102511.
[8] W. Z. Mao et al. *Phys. Rev. Res.* 5 (2023), L022047.
[9] P. Piovesan et al. *Nucl. Fusion* 57.7 (2017), 076014.
[10] W. Boyes et al. *Nucl. Fusion* 64.12 (2024), 124005.
[11] A. Burckhart et al. *50th EPS Conf. Plasma Phys.* (2024).
[12] A. Bock et al. *This conference* (2025).
[13] I. Krebs et al. *49th EPS Conf. Plasma Phys.* (2023).

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.