MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK

Stellarator DEMO Physics Gaps

MHD Equilibrium and Stability

K. Aleynikova[1], J. Geiger[1], J. Loizu[2], A. Alonso[3]

[1]Max-Planck-Institut für Plasmaphysik, EURATOM Association,
Greifswald, Germany
[2]École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
[3]Laboratorio Nacional de Fusi.n, CIEMAT, Madrid, Spain

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.

1. High-Beta MHD Stability and Ballooning Modes

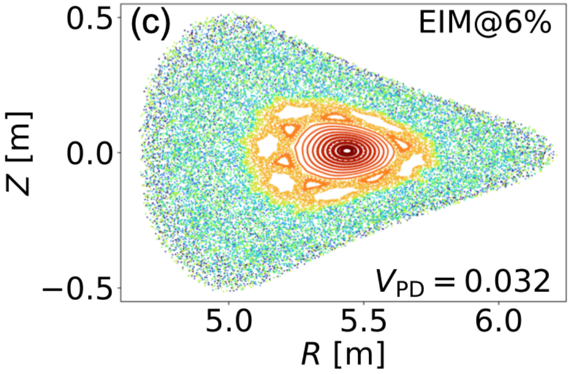

Figure 1: A snapshot of a Poincaré plot illustrating that the plasma persists beyond the expected ideal MHD stability limit *[Y. Zhou, K. Aleynikova, C. Liu, et al., Physical Review Letters, vol. 133, no. 13, 135102 (2024)].*

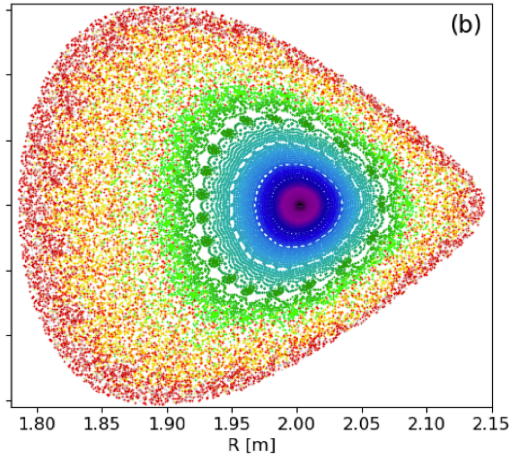

Figure 2: Though the degree of ergodization varies over the simulation time, the plasma core survives even the period of worst confinement (b, t = 0.421 ms) *[R. Ramasamy, K. Aleynikova, Nikita Nikulsin, et al. Nuclear Fusion 64, no. 8, 086030 (2024)].*

- Achieving and maintaining high-beta operation is essential for efficient plasma confinement and reactor performance.
- Our current understanding of beta limits in 3D magnetic configurations is incomplete for predictive design.
- In particular, the operational meaning and control of soft limits remain unclear across different stellarator configurations.

>> Advance the **predictive capability for high-beta** stability limits in 3D systems, by integrating theory, simulations, and experimental observations.

>> Develop operational strategies to **safely approach soft beta limits**, based on a better understanding of mode evolution, and their impact on confinement.

Relevance	Understanding and controlling high-beta operation is crucial for reactor performance and optimization.
Urgency	Urgent. Safe high-beta operation is important for stellarators to work well and be cost-effective.
Effort	Requires detailed theory-experiment comparison, expanded simulation efforts and identification of configuration-dependent stability margins. Predictive models are necessary.

2. Current-Driven Plasma Terminations in Stellarators

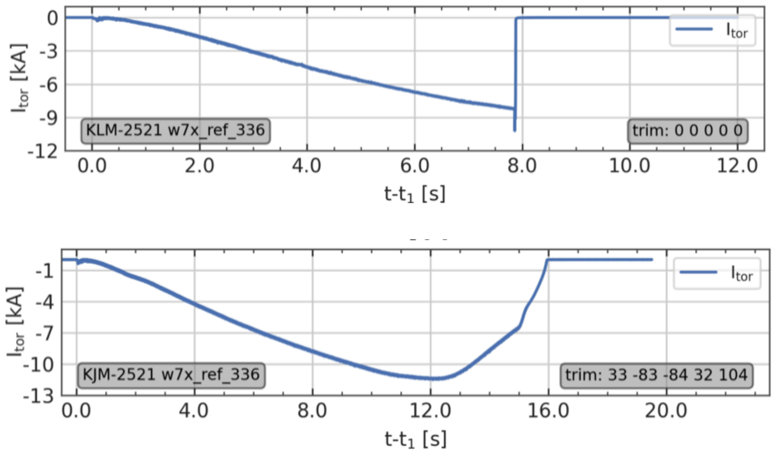

Figure 3: Toroidal current vs time, termination dynamics in W7-X, different configurations and different ECCD settings.

- W7-X has observed plasma termination events triggered by Electron Cyclotron Current Drive (ECCD) modifying the rotational transform profile.
- The effect of bootstrap current at high beta stability and plasma termination events remain uncertain, presenting potential operational constraints.
- A robust predictive capability to understand and prevent these termination scenarios is crucial for safe, continuous stellarator operation.

>> Develop predictive tool(s) to determine stability thresholds for current-modified equilibria, **clarify operational limits to prevent plasma termination** events.

>> Dedicated experiments on existing machines will be needed to benchmark such a tool/ model against experimental data.

Relevance	Stable current-driven operation significantly impacts stellarator viability, especially as reactor scenarios inherently involve a complex interplay of ECCD and residual bootstrap currents at high beta.
Urgency	Urgent, but can be carried out in parallel with the reactor design. Development of predictive capabilities is important to ensure safe and reliable reactor operation by preventing unexpected plasma terminations.
Effort	Requires comprehensive experimental campaigns combined with advanced theoretical modeling and stability analyses to accurately extrapolate from current experiments to reactor conditions.

3. Linear vs Nonlinear MHD Stability

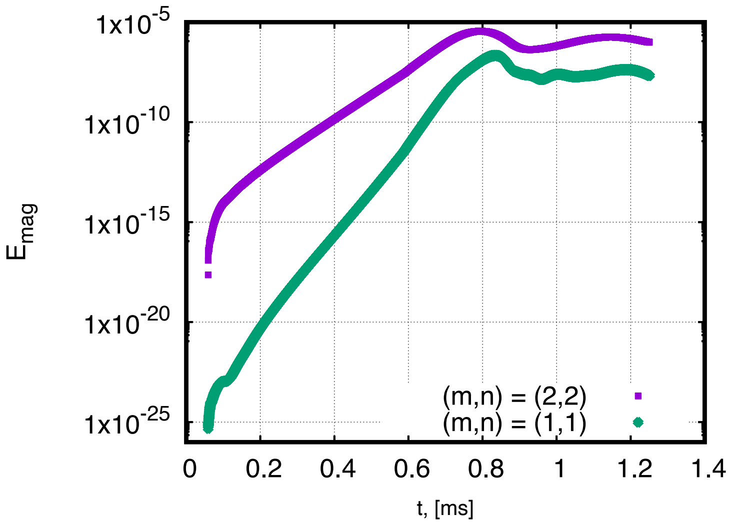

Figure 4: Time evolution of magnetic energy for two modes, showing distinct growth rates and nonlinear saturation behaviour.

- Current optimization processes typically rely on linear stability metrics, which may fail to accurately predict nonlinear plasma behavior.
- Nonlinear phenomena such as, for example, mode saturation or nonlinear mode coupling and interactions significantly affect plasma stability but are not captured by linear analyses.
- This gap introduces uncertainties into reactor designs, particularly at operational limits where nonlinear effects dominate.

>> Implement **nonlinear stability metrics** into design and optimization tools, backed by rigorous experimental validation and numerical simulations (or at least highlight validity of linear ones).

>> Improve understanding of nonlinear mode interactions and saturation dynamics, providing clearer operational boundaries and more **accurate stability predictions**.

Relevance	Reliable reactor design demands confidence in stability assessments beyond linear approximations, directly impacting safe operational limits and reactor efficiency.
Urgency	Urgent. Integrating nonlinear stability analyses early in reactor design is crucial to prevent unforeseen instabilities during operation.
Effort	Significant theoretical, computational, and experimental efforts are required to assess nonlinear phenomena and integrate them into practical stability evaluations.

4. Integrated Core-Edge MHD Stability

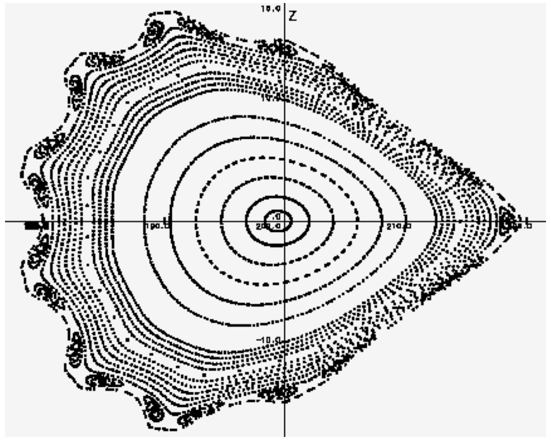

Figure 5: Poincaré plot (vacuum case) of the magnetic surfaces in W7-AS; island structures can form at the plasma edge, making it harder for the edge transport barrier to develop. [*Hirsch, M., et al. Plasma Physics and Controlled Fusion 42.5A (2000): A231*].

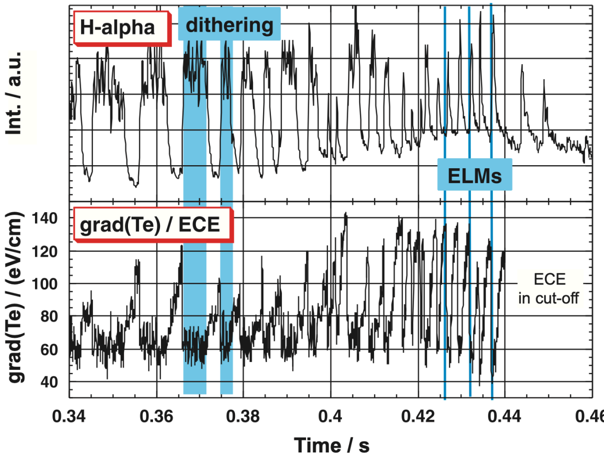

Figure 6: Behaviour of plasma edge parameters during a transition to H mode [*Hirsch, M., et al. Plasma Physics and Controlled Fusion 42.5A (2000): A231*].

- Core MHD instabilities influence edge and divertor plasma stability, and edge phenomena can affect core plasma performance.
- This coupling between core and edge MHD behaviors is currently poorly understood.
- Reliable global predictive modeling tools capturing these core-edge interactions are lacking, limiting effective design and operation.

>> Develop global models (and validate them on existing machines) capable of accurately simulating the coupled core-edge MHD interactions, including mode propagation, coupling dynamics, and heat flux effects.

Relevance	Understanding integrated core-edge stability is crucial to prevent unforeseen instabilities in reactor-scale plasmas, which could significantly compromise performance and safety.
Urgency	Medium urgency; can be investigated in parallel with the reactor design.
Effort	Experimental validation and sophisticated modeling efforts to characterize and predict complex interactions across core-edge plasma regions.

5. Divertor Topology Resilience

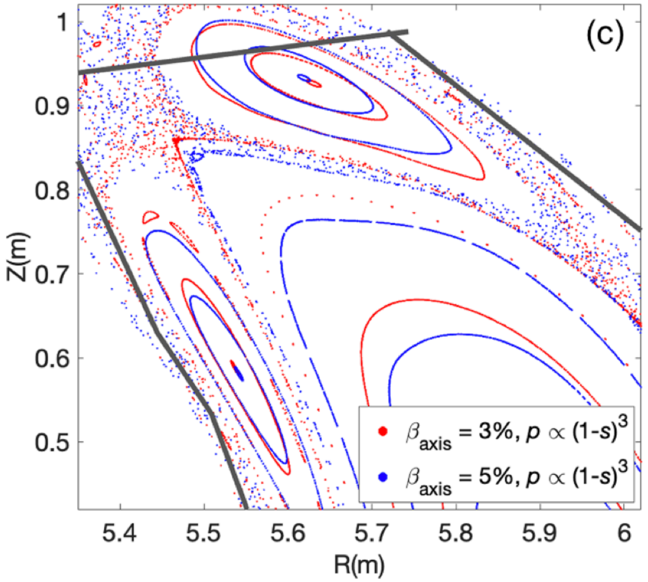

Figure 7: Poincaré plot illustrating a poloidal shift of the magnetic island due to finite-beta effects *[S. Xu, Y. Liang, A. Knieps, S. Zhou, Y. Feng, D. Reiter, Y. Suzuki, M. Jia, J. Geiger, F. Reimold et al., Nuclear Fusion, vol. 63, no. 6, 066005 (2023)].*

- The robustness of divertor magnetic topology against variations in equilibrium parameters (such as beta, plasma currents) in optimisation loops is not sufficiently predictable.
- Current design and optimization tools lack reliable, rapid metrics to assess divertor topology stability (may significantly affect, for example, exhaust efficiency, and overall reactor safety).

>> Develop robust predictive tools and metrics for **assessing divertor topology resilience rapidly and reliably** within design optimization workflows.

>> Investigate **sensitivity of divertor magnetic topologies to plasma parameter changes** (e.g., beta variations, induced currents), focusing on defining stable operational windows.

Relevance	Stable divertor configurations are essential for maintaining consistent reactor performance, protecting components, and ensuring long-term operational safety and efficiency.
Urgency	Urgent. Robust and rapid resilience evaluation tools are needed for informed optimization.
Effort	Requires integrating simulations with experimental validation, developing sensitivity analyses, and defining clear quantitative metrics for divertor topology resilience.

6. Advanced Equilibrium Solvers

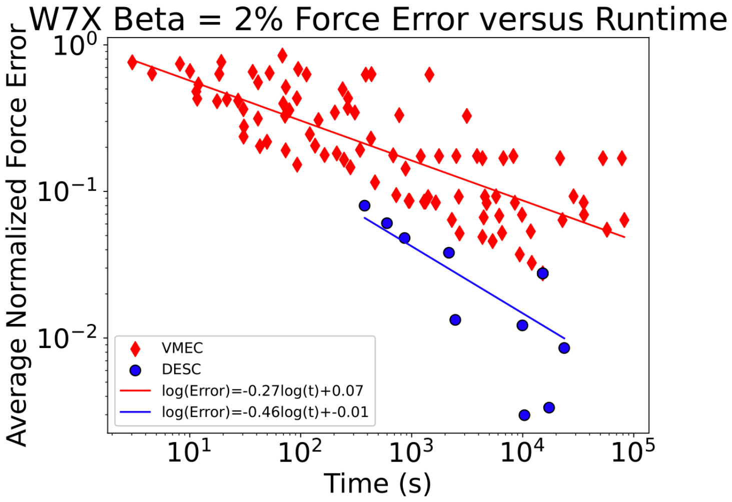

Figure 8: Solver convergence and complexity *[D. Panici, R. Conlin, D. W. Dudt, K. Unalmis, and E. Kolemen, Journal of Plasma Physics, vol. 89, no. 3, 955890303 (2023)].*

- Equilibrium calculations underpin nearly all stellarator design and analysis efforts.
- Accurate and rapid equilibrium solvers are essential for optimizing stellarator design, performance prediction, and scenario development.
- Current codes face trade-offs between computational speed and accuracy, particularly in the presence of magnetic islands and non-nested flux surfaces.

>> Develop next-generation equilibrium solvers that maintain **high accuracy while keeping the calculations fast** for large parameter spaces and complex geometries.

>> Clarify the scope and **limitations of existing solvers** (e.g., VMEC, GVEC, DESC), and evaluate when extended models (e.g., incorporating kinetic effects) become necessary.

Relevance	Improved solvers will impact optimization, control, and predictive capabilities.
Urgency	Medium urgency; with expanding experimental data and design complexity, solvers must evolve to support faster, more realistic simulations.
Effort	Requires algorithm development, code benchmarking, and rigorous testing in configurations with islands, stochasticity, and near-separatrix behavior.

Gap ID	Description	Relevance (1–3)	Urgency (1–3)	Effort Required (1–3)	Total Score	Priority
1	Understanding and predicting high-beta MHD and ballooning stability limits in 3D	3	3	2	8	High
2	Understanding current-driven plasma terminations and bootstrap current effects	2.5	3	1.5	7	Medium-High
3	Bridging gap between linear and nonlinear MHD stability for reliable design metrics	3	3	2	8	High
4	Integrated core-edge MHD stability	2	2	2	6	Medium
5	Divertor topology resilience to equilibrium variations (beta, currents) in optimisation loops	2	3	2	7	Medium-High
6	Development of advanced equilibrium solvers balancing speed and accuracy	3	1	2	6	Medium