Pressure effects on the topology of magnetic fields in stellarators

A. Baillod[1], J. Loizu[1], J. P. Graves[1], R. Jorge[2], A. Cerfon[3],
D. Malhotra[3], J. Schilling[2], Z. Qu[4], M. Landreman[5]

[1]École Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), Switzerland

[2]Max-Planck-Institut für Plasmaphysik, Euratom Association, D-17491 Greifswald, Germany

[3]Courant Institute, New York University 251 Mercer St, New York, NY 10012, USA

[4]Mathematical Sciences Institute, the Australian National University, Canberra ACT 2601, Australia

[5]University of Maryland, College Park, MD, 20742, USA

Three dimensional magnetic equilibria are in general composed of nested flux surfaces, magnetic islands and chaotic field lines, although it is possible to design stellarator coil configurations that produce vacuum fields with nested flux surfaces [1]. At finite β however, currents self-generated by the plasma, such as diamagnetic, Pfirsch-Schlüter or bootstrap, perturb the magnetic field, thus breaking nested flux surfaces and ultimately impairing confinement. To date, there is no theory, nor extensive numerical study that characterizes the maximum achievable β above which magnetic surfaces are destroyed, nor a theory on the dependency of this critical β on other relevant operational parameters. We propose using the Stepped Pressure Equilibrium Code (SPEC) [2], which can compute 3-dimensional stepped-pressure equilibria with magnetic islands and chaos, to study the effect of finite β on the magnetic topology of stellarators. Recent numerical work significantly improved the speed and robustness of SPEC [3], which allows large parameter scans in a reasonable amount of time [4]. In addition, SPEC has recently been extended to allow free-boundary calculations [5] with prescribed net toroidal current profiles [6]. Leveraging these new capabilities, we present here the first extensive and comprehensive study of the equilibrium β-limit with bootstrap current. We consider a number of representative configurations, such as classical, quasi-axisymmetric and quasi-helically symmetric stellarators. We provide a theoretical understanding of these β-limits by extending analytical stellarator expansions [7] and we identify the main operational parameters that determine these β-limits. Finally, it is shown that magnetic islands' width and chaotic magnetic field lines that are present in certain equilibria can be reduced or even suppressed via a precise optimization procedure using the SIMSOPT code [8].

This work has been carried out within the framework of the EUROfusion consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission. This work was also supported by a grant from the Simons Foundation/SFARI (No. 560651, A.B.).

References

[1] Pedersen, S. T. et al. 2016, *Confirmation of the topology of the Wendelstein 7-X magnetic field to better than 1:100,000*, Nature communications, **7**, 13493

[2] Hudson, S. R. et al. 2012, *Computation of multi-region relaxed magnetohydrodynamic equilibria*, Physics of Plasmas, **19** (11), 112502

[3] Qu, Z., et al. 2020, *Coordinate parametrization and spectral method optimisation for Beltrami field solver in stellarator geometry*, Plasma Physics and Controlled Fusion, **62**, 124004

[4] Loizu, J., et al. 2017, *Equilibrium β-limits in classical stellarators*, J. Plasma Phys., **83**, 715830601

[5] Hudson, S. R. et al. 2020, *Free-boundary MRxMHD equilibrium calculations using the Stepped-Pressure Equilibrium Code*, Plasma Physics and Controlled Fusion, **62** (8), 084002

[6] Baillod, A., et al. *Computation of multi-region, relaxed magnetohydrodynamic equilibria with prescribed toroidal current profile*, accepted for publication by Journal of Plasma Physics.

[7] Freidberg, J., 2014, *Ideal MHD*, Cambridge University Press (CUP), Cambridge, 9780511795046

[8] Simsopt development team, *Simsopt: A python framework for stellarator optimization*, 2021, 10.5281/zenodo.4741269.