9th Asia-Pacific Conference on Plasma Physics, 21-26 Sep, 2025 at Fukuoka

Optimizing omnigenity like quasisymmetry for stellarators

Hengqian Liu[1], Guodong Yu[1], Caoxiang Zhu[1] and Ge Zhuang[1]

[1] Department of Plasma Physics and Fusion Engineering, University of Science and Technology of China

e-mail (speaker): hengqianliu@mail.ustc.edu.cn

Omnigenous magnetic fields, where the bounce-averaged radial drift vanishes [1], offer a promising solution to confine charged particles in fusion devices, particularly in stellarators. However, non-quasisymmetric omnigenity has remained underexplored due to the absence of a general optimization method. We introduce a novel approach for optimizing omnigenity. With simplicity comparable to quasisymmetry (QS) optimization, the new method unifies both QS and non-QS omnigenity optimization and can be further generalized to optimize configurations beyond omnigenity. Precisely omnigenous configurations with exceptional confinement and unprecedented compactness have been realized. Moreover, novel configurations like pseudosymmetry [2] and piecewise omnigenity [3] have been directly optimized for the first time. These advances enable efficient explorations of practical stellarator designs with enhanced confinement and engineering feasibility.

Building on this framework, we employ the OOPS method [4] in SIMSOPT to generate three high-fidelity omnigenous equilibria – toroidal, poloidal (quasi-isodynamic) and helical – all obtained from a cold start and achieving aspect ratios A=6-8. Their omnigenity residues $\frac{1}{\mathcal{J}}\frac{\partial \mathcal{J}}{\partial \alpha}$ are two orders of magnitude lower than those of the W7-X high-mirror configuration, effective-ripple values render neoclassical transport negligible, and $\alpha-$particle loss fractions fall below 0.5% when scaled to ARIES-CS reactor dimensions. By slightly relaxing the optimization metric, we additionally obtain—again for the first time—directly optimized pseudosymmetric equilibria, which abandon the strict omnigenity condition yet are shaped so that locally trapped particles are largely prevented from forming, and piecewise-omnigenous equilibria, in which the global geometric constraints of omnigenity are loosened but omnigenous-level confinement is recovered by enforcing the condition $\mathcal{J}_1 + \mathcal{J}_2 = \mathcal{J}_3$ only within selected spatial regions. Both offer reduced elongation and improved coil-complexity proxies without compromising transport. The OOPS strategy therefore opens a contiguous design space that spans QS, exact omnigenity and its controlled violations, furnishing a practical route to compact, high-performance stellarators suitable for reactor applications and near-term experimental tests.

References

[1] L. S. Hall and B. McNamara, Three-dimensional equilibrium of the anisotropic, finite-pressure guiding-center plasma: Theory of the magnetic plasma, The Physics of Fluids 18, 552 (1975).

[2] M. Yu. Isaev, M. I. Mikhailov, D. A. Monticello, H. E. Mynick, A. A. Subbotin, L. P. Ku, and A. H. Reiman, The pseudo-symmetric optimization of the National Compact Stellarator Experiment, Physics of Plasmas 6, 3174 (1999).

[3] J. L. Velasco, I. Calvo, F. J. Escoto, E. Sánchez, H. Thienpondt, and F. I. Parra, Piecewise Omnigenous Stellarators, Physical Review Letters 133, 185101 (2024).

[4] Hengqian Liu, Guodong Yu, Caoxiang Zhu and Ge Zhuang, Optimizing omnigenity like quasisymmetry for stellarators, arXiv:2502.09350(2025).

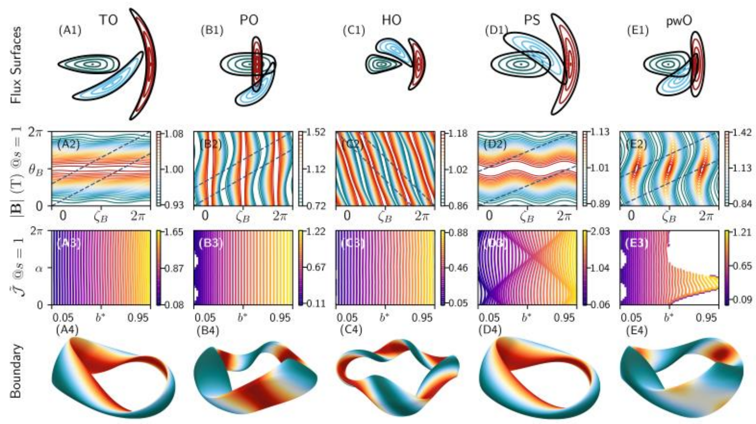

Figure 1. Gallery of optimized configurations. Column A: toroidal omnigenity, Column B: poloidal omnigenity, Column C: helical omnigenity, Column D: pseudosymmetry, and Column E: piecewise omnigenity. The first row shows cross-sections of LCFS and Poincáre plot from SPEC. The second row displays the |B| on LCFS in Boozer coordinates. The third row presents the normalized second adiabatic invariant $\mathcal{J}$ on LCFS. The fourth row illustrates the 3D plasma boundary shape.