A NOVAL METHOD TO OPTIMIZE OMNIGENITY LIKE QUASISYMMETRY FOR STELLARATORS

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1. INTRODUCTION

Stellarators utilize three-dimensional magnetic fields from external coils to stably confine plasma without large plasma currents. Carefully optimized stellarators have obtained high fusion performance comparable to tokamaks, making stellarators a promising pathway to fusion energy [1]. The magnetic field is commonly optimized to be omnigenous, where the bounce-averaged radial drift vanishes for trapped particles. Omnigenity is closely linked to the second adiabatic invariant, $\mathcal{J}$. In omnigenous fields, $\mathcal{J}$ is constant on the flux surface. There is a subset of omnigenity called quasisymmetry (QS). The magnetic field strength of QS configurations depends on a single angle in Boozer coordinates, ensuring symmetry in B that conserves the canonical angular momentum of particles. QS optimization is relatively simple and robust. A standard way is to reduce the asymmetric components in Boozer coordinates. The simplicity of QS optimization has led to great success. In contrast, non-QS omnigenity—despite being a less restrictive condition—remains underexplored, primarily due to the lack of similarly simple optimization methods. B contours in omnigenous fields are not straight in either equilibrium code coordinates or Boozer coordinates.

We introduce a novel approach for optimizing omnigenity. With simplicity comparable to QS optimization, the new method unifies both QS and non-QS omnigenity optimization and can be further generalized to optimize configurations beyond omnigenity. This approach has led to the realization of precisely omnigenous configurations with exceptional confinement and unprecedented compactness.

2. METHODOLOGY

Like QS, omnigenity can be optimized by minimizing asymmetric components, $f_{\text{omni}} = \sum_{m\neq0}\left(B_{m,n}/B_{0,0}\right)^2$, where $B(\alpha,\eta) = \sum B_{m,n}\cos(m\alpha - n\eta)$ and $B_{m,n}$ are Fourier coefficients. (α,η) coordinates are from a coordinate transformation similar to the Cary-Shasharina mapping [3]. The modified coordinate transformation constructs an exact omnigenous field from a (α,η) coordinate system where α is the field line label and constant η contours represent B contours. Therefore, the constructed ideal omnigenous field will satisfy $\partial B\ /\ \partial\alpha = 0$. When the actual equilibrium deviates from the ideal field, transforming the magnetic field strength back to the original (α, η) coordinates will yield curved contours. In analogy to QS optimization, using (α,η) coordinates as the general basis and reducing the symmetry-breaking modes will lead to omnigenity. While designed for non-QS omnigenity optimization, the coordinate transformation can be generalized to optimize QS and concepts beyond omnigenity, like pseudosymmetry (PS) and piecewise omnigenity (pwO).

3. RESULTS

Numerical examples of precisely omnigenous stellarators with excellent confinement and low aspect ratios have been obtained using the newly implemented cost function in SIMSOPT. Three vacuum configurations representing toroidal (TO), poloidal (PO), and helical omnigenity (HO) are optimized on the outermost magnetic surface, subject to aspect ratio (Ap) and rotational transform (ι) constraints. Fig. 1 shows the equilibria, with all configurations scaled to a volume-averaged field strength of 1 T and a major radius of 1 m. TO has Nfp=2, Ap=6, $\iota = 0.7$, PO has Nfp=3, Ap=6.5, $\iota \in [0.76, 0.87]$, and HO has Nfp=4, Ap=8, $\iota \in [1.19, 1.30]$. The optimized configurations are verified to have continuous nested magnetic surfaces throughout the volume.

All three configurations demonstrate precise omnigenity, leading to exceptional confinement in both collisional transport and collisionless alpha particle losses. As shown in Fig. 2, the effective ripple for the three configurations is orders lower than W7X. When scaled to the reactor size, the loss fractions of alpha particles in TO and HO are 0.50% and 0.16%, respectively, while PO has no losses before the slowing-down time, achieving the best performance among the proposed designs (comparable to precise QS [4]). In particular, the aspect ratios are lower than any existing omnigenous configuration (TO: 6.0 vs 19.6, PO: 6.5 vs 8.0, HO: 8.0 vs 18.3), which will substantially reduce the construction cost.

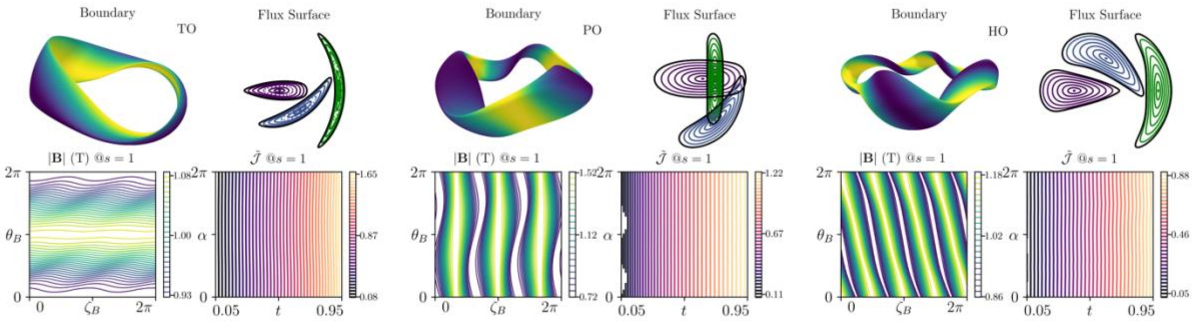

Fig. 1 Boundary shapes, flux surfaces, B contours, and $\mathcal{J}$ distributions of TO (left), PO (mid), and HO (right).

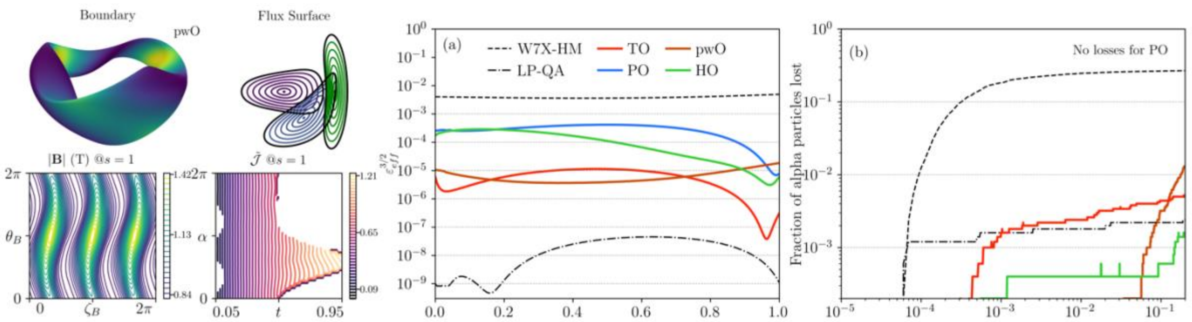

Fig. 2 The pwO configuration (left), the neoclassical transport coefficient (mid), and the alpha particle losses (right).

The pwO concept arises from $\partial\mathcal{J}/\partial\alpha = 0$ being fulfilled piecewisely [5]. explaining good confinement in configurations deviating from exact omnigenity. Here, we present the first direct optimization of pwO. We restrict the range of η (e.g., $\eta \in [-\pi/2, \pi/2)$) in the coordinate transformation to enforce intersections between adjacent B_{max} contours. Fig. 2 left illustrates a PO-like pwO configuration with Nfp=3, Ap=6, $\iota_{\mathrm{edge}} = 0.62$. The obtained configuration combines omnigenity (in the low-field region) and pwO (in the high-field region). It achieves low neoclassical transport and alpha-particle loss fractions (~1%) at reactor scale, making it a promising candidate for future reactors.

4. SUMMARY

We have introduced a novel method for optimizing omnigenity by reducing symmetry-breaking modes, conceptually as simple as the QS optimization. Using this approach, precisely omnigenous configurations distinct from QS have been obtained, exhibiting excellent neoclassical confinement and low alpha-particle losses. Notably, TO and HO have significantly lower aspect ratios than previously reported configurations, making them promising candidates for future stellarators. For the first time, PS and pwO configurations with low neoclassical transport and reduced elongation have been directly optimized.

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