Geometric Stabilization of Stellarator Magnetic Fields via 6-Fold Interlaced Helical Symmetry

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Abstract

This paper presents a concept study on a novel stellarator coil topology based on a 6-fold ($N=6$) "Interlaced Helix" symmetry . The design emerged from a computational dialogue utilizing advanced Large Language Models to apply geometric efficiency principles (Kelvin Packing) to magnetic confinement . Unlike conventional modular designs, this topology leverages a continuously interlaced winding scheme . While $N=6$ symmetries historically pose challenges regarding low-order rational resonances, preliminary geometric analysis suggests that the specific "Interlaced" topology induces high magnetic shear, potentially facilitating intrinsic error-field compensation (Geometric Mode Cancellation) . The study aims to present this AI-derived geometry for physical validation via MHD equilibrium codes .

1. Introduction

The optimization of stellarator magnetic fields typically involves a trade-off between engineering complexity and magnetohydrodynamic (MHD) stability . Current advanced stellarators, such as Wendelstein 7-X, often favor $N=5$ symmetry to avoid dangerous low-order resonances (e.g., $n/m = 1/1$) that can lead to magnetic island formation . However, geometric partitions of 3D space (such as the Kelvin cell structure) suggest that 6-fold symmetries offer superior packing properties . This study investigates a 6-fold interlaced magnetic topology, hypothesizing that the resonance risks in $N=6$ systems can be mitigated by the strong magnetic shear generated through the intrinsic "weaving" of the coils .

2. Design Methodology: AI-Assisted Exploration

2.1 From Biomimicry to Kelvin Packing

The topology described herein is not derived from traditional optimizer codes (like ROSE or VMEC), but from a geometric approach initially inspired by biological redundancies . Further analysis identified a strong correlation with the Kelvin Cell structure (Tetrakaidecahedron), which represents an optimal partition of 3D space with minimal surface area. The AI models converged on this 6-fold interlaced geometry as a method to map this high-efficiency packing onto a toroidal magnetic field, aiming to minimize flux surface distortion through symmetry cancellation .

2.2 Design Parameters

The proposed design utilizes a continuous helical coil system wound around a toroidal surface :

- **Major Radius (R_0):** 5.5 m
- **Minor Radius (a):** 1.5 m
- **Symmetry (N):** 6 (Hexagonal)
- **Winding:** 6 independent helices, 8 poloidal turns per transit .

2.3 The Interlaced Algorithm

The core innovation lies in the phase-locked winding. The trajectory of the h-th helix ($h \in [0,5]$) is defined by a strict phase offset $\delta_h = (h/6) \cdot 2\pi$.

To induce magnetic shear, a geometric radial modulation is applied along the toroidal angle ϕ (replacing the temporal parameter t from initial drafts):

$$r(\phi) = a \cdot [1 + \epsilon \cdot \sin(6\phi + 2\delta_h)]$$
with $\epsilon = 0.15$. This creates a static geometry where opposing helices exhibit counter-phase radial excursions .

3. Theoretical Stability & Challenges

3.1 Geometric Mode Cancellation

Instead of wave interference, this design aims for Harmonic Cancellation in the magnetic field error spectrum . By winding coil pairs $(1,4)$, $(2,5)$, and $(3,6)$ in strict anti-phase, specific resonant Fourier components of the magnetic field error (B_{nm}) are hypothesized to cancel out purely due to geometric symmetry .

3.2 Addressing the $N=6$ Resonance Issue

A known critique of 6-fold symmetry is the proximity to natural resonances (e.g., $\iota = 1$) .

- **Challenge:** Standard $N=6$ designs often suffer from island formation at these rational surfaces.
- **Hypothesis:** The "Interlaced" topology creates a highly twisted flux tube, generating strong **Magnetic Shear** ($\hat{s} = (r/\iota)(d\iota/dr)$) . High shear is a known mechanism to "smear out" resonances and suppress the growth of magnetic islands .

3.3 Engineering Implications

We acknowledge that an interlaced topology presents significant manufacturing challenges compared to modular coils . Specifically, the Lorentz forces at the crossover points of the helices are expected to produce high localized shear stress on the conductor insulation.

- **Mitigation Strategy:** The potential need for complex inter-coil support structures is recognized. However, if the stability benefits of the continuous helix prove superior in simulations, these engineering hurdles may be justified by the simplification of the overall magnetic configuration (elimination of active trim coils) .

4. Preliminary Results & Open Source Initiative

The geometric ray-tracing simulation demonstrates :

- **Closed Topology:** Formation of a toroidal cage without visible loss cones .
- **Shear Generation:** Visual confirmation of high torsion in the field lines due to the modulation factor ϵ .

Conclusion

The 6-fold Interlaced Helix represents a high-risk, high-reward "middle ground" between continuous helical coils (LHD) and modular optimization (W7-X) .

To foster rapid validation, the complete geometry, code, and parameter sets are released as Open Source Hardware . We explicitly invite the fusion community to subject this topology to rigorous MHD analysis using VMEC or SPEC codes to determine if the predicted shear is sufficient to overcome the intrinsic $N=6$ resonances .