

Exploratory Study: 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 (Gemini 3, Claude Opus 4.5) to apply biological redundancy principles 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 the dangerous $n/m = 1/1$ and $1/2$ resonances that can lead to the formation of large magnetic islands and confinement degradation.

However, structural principles observed in nature (hexagonal packing) suggest that 6-fold symmetries offer superior packing density and redundancy. This study investigates a **6-fold interlaced magnetic topology**. The central hypothesis is that the increased risk of resonance in $N=6$ systems can be mitigated not by external correction coils, but by the strong magnetic shear generated through the intrinsic "weaving" of the coils.

2. AI-Assisted Geometric Exploration

2.1 Concept Origin

The topology described herein is not derived from traditional optimizer codes (like ROSE or VMEC), but from a geometric approach inspired by hypothetical biological structures (Hexa-DNA). Two separate state-of-the-art AI models independently converged on a 6-fold symmetry with an interlaced winding pack as a potential solution to minimize geometric error fields through symmetry cancellations.

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 (Hexa-Symmetry)
- **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 radial modulation factor ("Breathing Mode") is applied:

$$r(t) = a \cdot [1 + \epsilon \cdot \sin(6\phi + 2\Delta_h)]$$
with $\epsilon = 0.15$. This creates a geometry where opposing helices oscillate in counter-phase.

3. Theoretical Stability & Challenges

3.1 Geometric Mode Cancellation

Instead of "destructive interference" (wave mechanics), this design aims for Harmonic Cancellation in the magnetic field spectrum. By operating 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.
- **Proposed Solution:** The "Interlaced" topology creates a highly twisted flux tube. We hypothesize that this generates 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, potentially stabilizing the $N=6$ configuration.

3.3 Engineering Implications

We acknowledge that an interlaced topology presents significant manufacturing challenges compared to modular coils (e.g., assembly of interlocking components, Lorentz forces between adjacent conductors). However, if the stability benefits of the continuous helix prove superior in simulations, these engineering hurdles may be justified by the elimination of active feedback control systems.

4. Preliminary Results & Open Source Initiative

The geometric ray-tracing simulation demonstrates:

- **Closed Topology:** Formation of a closed 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).

Next Steps & Invitation

To foster rapid validation, the complete geometry, code, and parameter sets are released as Open Source Hardware. We 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.