Advancing the Concept of the Quasi-isodynamic Stellarator as the Basis for a Fusion Reactor

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The superconducting stellarator experiment Wendelstein 7-X (W7-X) has steadily achieved scientific milestones since its start of operation in 2015, broadly validating its design principles. These include confirmation of its neoclassical transport optimization [1, 2], record confinement (triple product), long-pulse operation, and stable detachment, confirming the reliable operation of the island divertor exhaust concept. Such successes make W7-X the natural model on which to build towards a fusion reactor concept. Still, its design has shortcomings, including insufficient fast-particle confinement and uncomfortably large bootstrap current. This can be blamed on the fact that it is not quasi-isodynamic (QI) to sufficiently high precision, having been designed before the term was even coined [3], and before the notion was fully understood. However, theory and stellarator optimization have sufficiently advanced, especially in recent years, such that designs are now being proposed achieving performance that, to the best of our understanding, means that they can seriously be considered as fusion reactor candidates [4, 5, 6]. In this talk we present novel QI stellarator designs, the methodology behind their optimization, and extensive evaluation of their properties.

Among the most mature are "Stable Quasi-isodynamic Designs" (SQuIDs) [6]; see Figure 1. These designs are found by a novel method that targets QI quality in conjunction with magnetohydrodynamic (MHD) stability and low turbulence. One such design [7] has been investigated thoroughly to demonstrate its suitability as a basis for a fusion reactor. Fixing a target volume-averaged plasma pressure of $\langle\beta\rangle = 0.02$, a number of checks were performed to assess the physics and performance of a potential device based on the design.

Global ideal-MHD ballooning stability is demonstrated for $\langle\beta\rangle \leq 0.03$, giving a safety margin with respect to the target operating point, and neoclassical calculations confirm a negligible bootstrap current of around 15 kA. This design is found to be compatible with filamentary coils, similar in complexity to those of W7-X, owing to the use of an additional coil complexity design criterion [8]. With a valid coil set, we investigate the presence and characteristics of edge magnetic islands, and find a related divertor solution suggesting acceptable heat loads could be achieved at reactor scale.

Of particular interest is the prediction of confinement, which must combine neoclassical transport with that from turbulence. Our turbulence optimization is based on three robust principles, based on well-studied physics: (1) reduced turbulence drive by flux expansion [9, 10], (2) increased zonal flow response [11], and (3) stronger and more complete maximum-J behavior [12]. Additionally, the possibility for an electron root transition has been incorporated into the optimization, meaning that an internal transport barrier might be induced by a strongly sheared radial electric field [13, 14].

To assess the turbulence optimization, we use gyrokinetic simulations combined with transport theory to calculate steady-state profiles and estimate global confinement, showing improvement as compared with the standard configuration of W7-X. This has practical consequence for reactors: we find that equal total fusion power could be achieved in the SQuID designs with a significant reduction in plasma volume.

Although it is critical to establish the feasibility of more established lines of stellarator designs, it is also important to continue the search for new QI concepts, which *e.g.* show substantial differences with regard to geometrical compactness, confinement properties, and build complexity. Such progress may ultimately enter decisively in determining the extent to which fusion power based on the stellarator is economical. To conclude, we therefore discuss new directions in QI optimization, from fundamental theoretical progress, to novel optimization methodology, that broadens the available optimization space.

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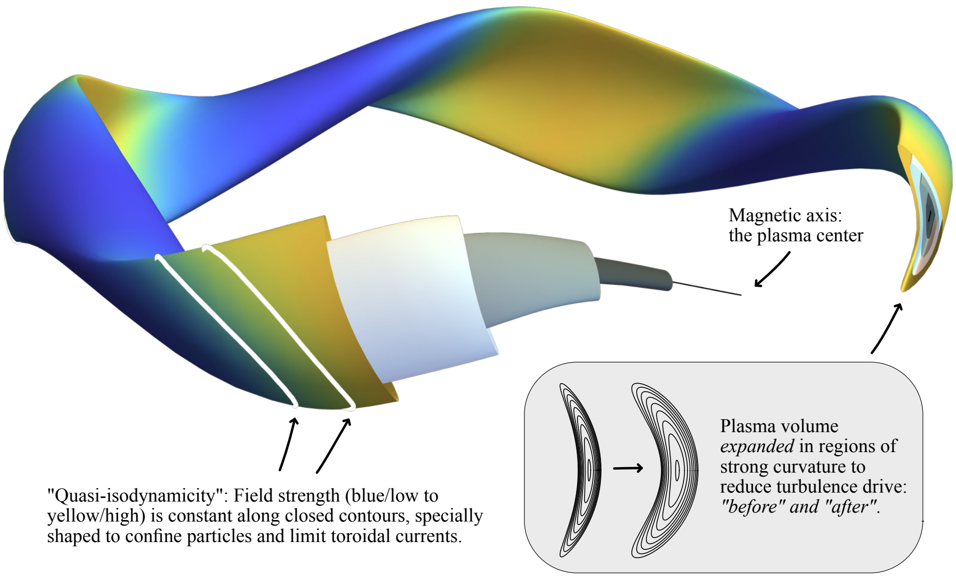

Figure 1: Anatomy of a SQuID: The geometry and optimization principles of a QI stellarator.

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