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Improving the Stellarator Through Theoretical Understanding

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Introduction: The stellarator is unique among magnetic confinement concepts in that the plasma performance is mostly determined by externally applied magnetic fields. There is considerable opportunity to improve the stellarator through increased understanding of how 3D fields impact important plasma physics processes, enabling innovation in configuration design. We review recent progress in stellarator theory in the topical areas: 1) improved energetic particle confinement, 2) affecting turbulent transport with 3D shaping, 3) novel optimization and design methods, 4) reducing coil complexity and 5) MHD equilibrium tools.

Energetic particle confinement: Energetic particle confinement is a key issue for the scalability of stellarators to fusion power plants. Analytically derived proxies for collisionless energetic particle confinement have been used for the first time in optimization schemes to produce quasi-helically symmetric stellarator equilibria that eliminate all collisionless losses within the plasma mid-radius for an ARIES-CS scale reactor. The analytic proxy accounts for the competition of net bounce-averaged radial drifts relative to poloidal drifts with the goal of aligning contours of the second adiabatic invariant J|| to magnetic surfaces. Using the coil optimization codes REGCOIL and FOCUS, it is possible to generate coil solutions for these configurations with sufficient fidelity that alpha particle confinement is not degraded, the key feature being to place the coils far enough away from the plasma to avoid high-order harmonic induced ripple losses.

Effect of 3D shaping on turbulent transport: Theoretical techniques produced stellarator configurations with reduced neoclassical transport as demonstrated in the HSX, LHD and W7-X experiments. As such, microinstability induced turbulent transport is the dominant transport channel in present day optimized stellarators. A frontier research area in stellarator optimization is to use 3D shaping of the magnetic field geometry to reduce turbulent transport.

Using analytic theory and gyrokinetic simulations, a regime of weak ITG/TEM is identified that applies to both stellarators and tokamaks. In specific geometries, turbulent transport can be reduced by one to three orders of magnitude as seen in W7X with pellets and many tokamak internal transport barriers. Appropriately optimized stellarators can access this regime over most of the minor radius, as identified in equilibria for the quasi-axisymmetric stellarator NCSX.

Nonlinear gyrokinetic studies demonstrate that mixing length estimates based on linear theory can be unreliable predictors for turbulent transport rates for the quasi-symmetric class of stellarators. This motivates a need to understand how 3D shaping affects turbulent saturation physics. The important nonlinear energy transfer mechanism is a coupling of linear instabilities to damped eigenmodes at comparable wave number through a three-wave interaction. As this mechanism is a strong function of 3D shaping, the geometric characteristics of different classes of stellarators strongly impact turbulent transport rates. In particular, the relatively short connection length of quasi-helically symmetric stellarators enables a very efficient nonlinear energy transfer channel to saturate turbulence at lower levels for a given instability drive.

Both analytic theory and nonlinear GENE simulations are being developed to describe the role of finite-beta on stellarator turbulence. Linear gyrokinetic simulations in HSX geometry show that kinetic ballooning modes (KBM) can be excited at beta values far below the threshold value predicted by ideal MHD ballooning theory at long wavelength. Nevertheless, significant nonlinear stabilization is observed at finite beta, with nonlinear simulations suggesting that coupling to marginally stable linear Alfvenic modes is an important property of the nonlinear saturation physics at beta values well below critical values for KBM onset. Additionally, global gyrokinetic simulations of finite-beta micro-turbulence can now be performed with the XGC code.

Optimization methods: Substantial progress has been made in optimization and design methods for stellarators. One instance is a new method to generate and parameterize quasi-symmetric and omnigenous plasma configurations using analytic expansions about the magnetic axis. This approach is orders of magnitude faster than traditional stellarator optimization, allowing wider surveys over parameter space, and enabling insights into the character of the solution set. These near-axis expansions have enabled the first combined plasma-and-coil optimization for quasi-symmetry that uses analytic derivatives.

Another area of progress is the development of adjoint methods for computing shape gradients. These techniques, widely used outside of plasma physics, allow shape derivatives to be computed extremely efficiently, enabling derivative-based optimization and sensitivity analysis. Adjoint methods have recently been demonstrated for many quantities of interest for stellarator design, including collisional transport and coil complexity.

Stellarator Coils: Recent advances in computational tools are enabling efforts to reduce coil complexity in optimized stellarators. The FOCUS code uses a fully 3-D representation that allows coils to move freely in space avoiding the need to introduce a winding surface as used in conventional coil optimization codes. This freedom allows more design space to be explored. FOCUS also employs analytically calculated derivative information for use in fast optimization algorithms and in direct assessment of global coil tolerances for error fields. Recent applications include using FOCUS for the design of new stellarator experiments and applications to innovations in magnet technology including permanent magnets and high field high-Tc superconductors.

MHD Equilibria Tools: The stepped-pressure MHD equilibrium code (SPEC) code has been developed for stellarator applications. SPEC employs a model using a sequence of sharp boundaries for which discontinuities in the pressure and magnetic field are present, and allows for relaxation and "tearing"at rational surfaces. Recent advances and applications include the development of a free-boundary capability, linear and nonlinear stability calculations, and the study of possible local relaxation events in W7-X.

Configuration Designs: Advances in physics understanding can be used to generate metrics for use in the stellarator optimization codes STELLOPT and ROSE. These advances are being employed to produce new stellarator configurations with excellent confinement properties.

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