Stellarator Physics

Stellarators are three-dimensional toroidal plasma confinement devices that rely on a numerically determined plasma surface shape in order to achieve optimized plasma confinement, stability, and steady-state operation. These devices have the potential of providing a low-cost path to the development of fusion power with a much lower risk of the current-driven disruptive instabilities that are present in tokamaks. Stellarator physics and simulation are of increasing interest in the U.S. Fusion program due to the fact that new experimental facilities will be built at several U.S. research centers. The stellarator devices that are either operating or in the planning/construction phase in the U.S. program target the three possible forms of quasi-symmetry (quasi-helical, quasi-toroidal, and quasi-poloidal). Quasi-symmetry implies that there is an ignorable coordinate present for the magnetic field strength (i.e., a direction in which the magnetic field doesn't vary significantly) when viewed within a particular set of coordinates. Fig. 1 shows devices (HSX, NCSX, and QPS) that have been designed based on these forms of quasi-symmetry. Due to their inherently three-dimensional nature, stellarators rely heavily on numerical simulation and computation. The optimized design and physics analysis of these devices would not be possible without access to high-performance parallel computers.

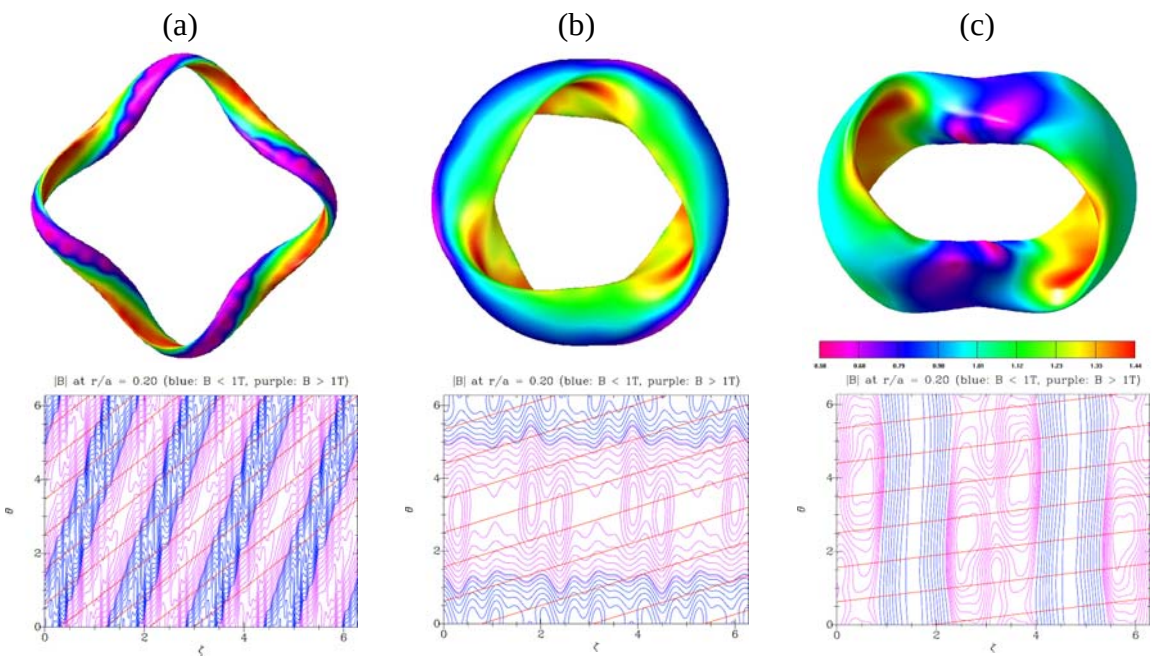

Figure 1 - Outer flux surfaces (top) with magnetic field strength color contours of devices with (a) quasi-helical, (b) quasi-toroidal, and (c) quasi-poloidal symmetry. The lower figures show contours of magnetic field strength for an interior flux surface in the transformed coordinates appropriate to quasi-symmetry for each device.

Three-dimensional configurational flexibility is one of the significant new features that stellarator experiments offer. Recent designs allow variation of currents in up to 10 different major coil groups; various smaller trim coils may also be present. However, the value of all this flexibility would be largely lost if it were not for powerful optimization codes that can find coil current combinations in this multi-dimensional parameter space that lead to improved plasma configurations. The STELLOPT code has been the primary tool used for both the design of recent stellarators and in flexibility studies. One example of the use of flexibility is in the reduction of magnetic islands. These are defects in the magnetic configuration that can be induced by a variety of sources such as small manufacturing or alignment errors in the magnetic coils, changes in coil geometry due to thermal or magnetic stresses, or internally by plasma instabilities. In the vicinity of magnetic islands the magnetic field lines no longer are confined to nested, closed toroidal flux surfaces. They move radially away from the initial equilibrium surfaces, leading to much more rapid plasma energy losses. Figure 2 shows an example of island suppression.

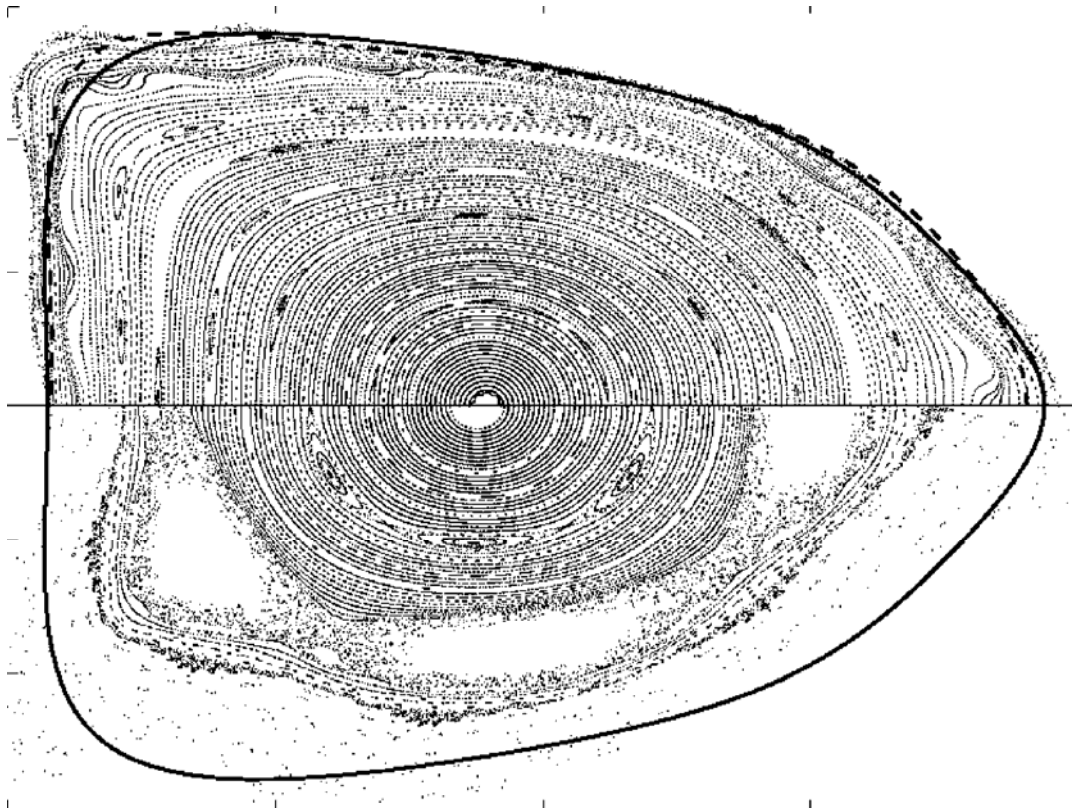

Figure 2 – PIES magnetic field puncture plot at at a fixed toroidal plane for the NCSX stellarator showing the initial state with sizeable magnetic islands (lower half) and the final state after optimization (upper half) with relatively small magnetic islands and nested, closed flux surfaces.

This example is based on an early coil design algorithm for the National Compact Stellarator Experiment (NCSX) that did not explicitly target resonant field reduction, and resulted in configurations with large magnetic islands. Subsequently, an optimizer was built around the PIES equilibrium code which modified the design of candidate coil sets to give good finite current, finite pressure flux surfaces, while preserving desired physics and engineering properties of the configuration. The optimizer was applied to obtain the reference coil set for NCSX. The figure shows the results of following the field lines for the NCSX coil set before (bottom half) and after (top half) the resonant field reduction process.

Computation of plasma equilibria is the first step both for the optimization and physics analysis of stellarators. The PIES equilibrium code can calculate full 3-D equilibria, including island regions. A second equilibrium code, VMEC that assumes nested closed flux surfaces, is also extensively used in the optimization and physics analysis of stellarators, due to its ability to rapidly calculate somewhat more approximate equilibria. The PIES code will be upgraded to include neoclassical transport effects on magnetic islands. Its efficiency will also be improved for 3-D equilibria with islands and stochastic regions so it can be used more routinely for analysis of experimental data.

Plasma transport is another computationally intensive physics area of importance for stellarators. Due to the three-dimensional nature of stellarator magnetic fields, analytic expressions for transport coefficients cannot be derived in general to the extent that has been possible for axially symmetric (tokamak) devices. Computational solutions have been developed both based on Eulerian localized transport codes, such as DKES as well as Lagrangian orbit-following Monte Carlo codes such as DELTA5D, GTC, and ORBIT. A shell code has recently been developed to run DKES in parallel over multiple flux surfaces with subsidiary loops over collisionality and electric field so that the extensive transport coefficient data bases required for each configuration can be more rapidly generated. In addition to predictions of cross-field transport of particles and energy, this type of calculation has also allowed prediction of plasma flow velocity moments within each magnetic flux surface (see Fig. 3). Such plasma flow predictions are of importance in understanding enhanced transport barriers (related to sheared flows) as well as allowing improved calculations of collisional bootstrap current and the ambipolar electric field. Future extensions of this moments method include applications to multi-species impurity transport and improvements in the calculation of the viscosity coefficients. The Monte Carlo codes have been developed to address non-local transport problems, such as energetic particle transport (neutral beam slowing-down, RF tail populations, fusion alpha particles) and transport in the presence of turbulent fluctuating fields. They have also been benchmarked against thermal neoclassical transport. Since they follow non-interacting particles (a test-particle/static field model is typically used), such codes are readily parallelized and can efficiently use large numbers of processors.

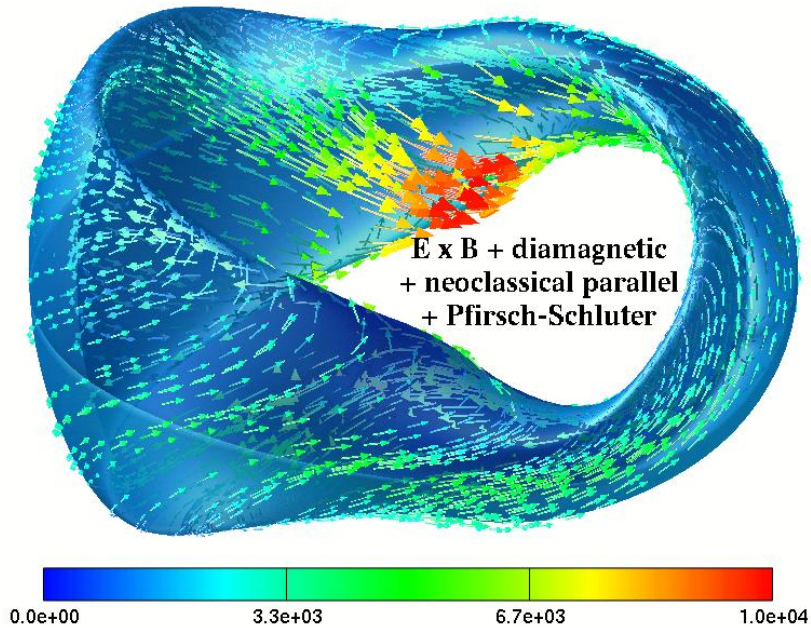

Figure 3 – Plasma velocity flow vectors on the outer flux surface of the QPS stellarator.

Plasma heating RF (radio frequency) heating is used extensively in stellarator experiments due to its low cost and high flexibility. New computationally intensive tools are under development to calculate the RF wave field and its plasma absorption for 3-dimensional systems. Although the wave fields enter the plasma initially at moderate wavelengths, they can become mode-converted and absorbed in local regions at much shorter wavelengths, resulting in strong couplings over a range of length scales.

Plasma stability is a final area of stellarator physics where access to high performance parallel computers is essential. Stability issues for compact stellarators include current-driven modes, short-scale-length pressure-driven ballooning modes, energetic-particle-driven instabilities, and plasma microturbulence. Several linear variational stability codes (TERPSICHORE, CAS3D, COBRA) for addressing current-driven and ballooning instabilities have been developed and are coupled into the optimization efforts. Resistive MHD and hybrid fluid-particle models are addresses by the M3D code which can follow the nonlinear evolution of large scale instabilities. M3D can also model linear and nonlinear energetic particle-driven modes. The STELLGAP code has been developed to calculate high resolution Alfvén gap structures for three-dimensional systems and to identify modes that can be driven unstable either by in situ energetic tails or by external antenna excitation.

The future computational needs of stellarator physics modeling activities are driven by the need for faster processors, increased memory per processor (2 Gbytes and above), improved turn-around time for parallel calculations, and continued use of systems with fast general parallel file systems (GPFS). The first two needs are driven by the highly computationally intensive nature of three-dimensional plasma configurations. Our ability to model the various physical processes in these systems is limited by processor speed,

and, in some cases, memory due the large amount of data that must be available to resolve even equilibrium (with multiple island chains) physics in stellarators. The need for rapid turn-around is driven by the fact that, although these codes have been adapted for parallel architectures, they haven't yet benefited from the many person-years of development that characterize more mature codes in other areas. Thus, there is more time spent in the debug/testing part of the coding cycle in stellarator computational research and more rapid turn around of moderate sized parallel jobs (up to 128 processors) is essential for progress in this area. Many of the parallel codes in this area (e.g., the STELLOPT code) use disk writes to preserve and pass large amounts of data around among a variety of heterogeneous subsidiary codes. Problems have been encountered when this code has been ported to clusters that do not support general parallel file systems. Therefore, it is critical that future NERSC systems continue to support GPFS and use techniques such as disk striping to maintain high performance disk access. A final administrative issue for future NERSC systems is that stellarator research is a very international activity and it is essential that good access be available to these systems from our international collaborators.