2.3 STELLARATOR THEORY

2.3.1Background and Scientific Issues

The goals of the stellarator theory research program at ORNL are to develop new theoretical models and computational tools for plasma confinement in 3D stellarator configurations. Our research encompasses the physics issues of stellarators with the three primary forms of magnetic symmetry (see Fig. 2.22): quasi-poloidal symmetry (QP), quasi-toroidal symmetry (QA) and quasi-helical symmetry (QH). This work is thus applicable to existing stellarator experiments (HSX – a QH stellarator) within the U.S. fusion program, as well as the recently proposed compact stellarator experiments (QPS, NCSX, CTH). In addition, we maintain collaborative connections with stellarator laboratories both in Europe and Japan.

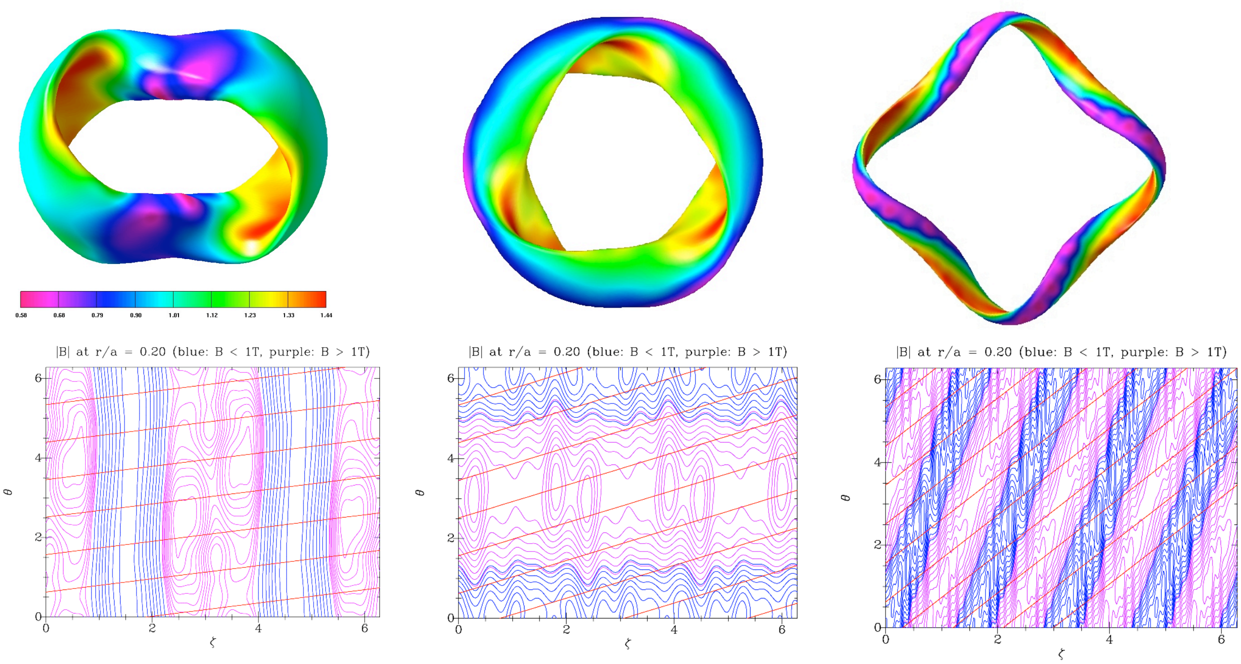


Fig. 2.22. Stellarators with the three primary forms of quasi-symmetry. Top figures show outer flux surface with color contours showing |B| variation. Bottom figures show |B| variation on a flux surface at $(\psi/\psi_{edge})^{1/2}$ = 0.2. Left-hand figures are for the QPS (QP-symmetric) device; middle figures are for the NCSX (QA-symmetric) devices; right-hand figures are for the HSX (QH-symmetric) device.

Much of our effort in previous years has been directed toward the development of a comprehensive physics/theory-based set of tools for optimizing [1] low-aspect-ratio stellarators and in physics analysis leading to the development of the QPS [2] and NCSX [3] designs. Now that the QPS and NCSX design configurations are fixed, our emphasis has shifted to looking more in depth at the physics issues and flexibility characteristics of these devices along with long lead-time code development efforts such as equilibrium reconstruction that will be essential for the future theory/modeling support of these devices. The physics topics that we are interested in include 3D equilibria, neoclassical transport, rf heating, MHD stability, edge physics, Alfvén mode stability, and energetic particle confinement. In addition, our efforts in stellarator optimization will continue due to interest in flexibility studies for QPS, a possible need for dynamically varying coil currents in order to suppress magnetic islands as the plasma β increases in QPS and NCSX, and our participation in compact stellarator reactor studies.

The physics properties and flexibility characteristics of compact stellarators have formed the primary foci of our stellarator theory efforts over the past several years. These devices offer the potential of an attractive fusion reactor with a lower-cost development path compared with the large-aspect-ratio approach. In addition, for near-term experimental devices, compact plasmas have larger transverse plasma dimensions (e.g., better neutral shielding) at a fixed cost than large-aspect-ratio stellarators. These facts have made low-aspect-ratio (A ~ 2 to 4) stellarator concepts a key ingredient of the U.S. fusion program for the foreseeable future. These configurations are also, at this time, a unique contribution to the world fusion effort and provide an opportunity to study stellarator physics in a new parameter space that includes finite bootstrap and Ohmically driven currents.

The U.S. program is pursuing compact stellarator configurations that are based on two main types of quasi-symmetry (i.e., symmetries of |B| in Boozer coordinates): the QPS (quasi-poloidal symmetry) and the NCSX (quasi–toroidal symmetry) configurations. Our theory effort is closely integrated with and supports both of these configurations. This has been true throughout the design process during which the Oak Ridge Stellarator Optimization Code (STELLOPT) and merged plasma-coil optimizer have been used extensively in the synthesis of both devices. The physics analysis and flux surface reconstruction tools that we have developed also have been and continue to be applied to both systems. Much of the stellarator design, optimization, and evaluation efforts have been funded by the QPS and NCSX projects. Also, the flux surface reconstruction work is funded under a separate project. Since there is a close coupling between these efforts and our theory-funded tasks, we shall describe all of these efforts to some extent in the following. Over the past three years our group has provided theory support for two successful Physics Validation Reviews (NCSX, March 26, 2001; QPS, April 24, 2001) and subsequent Conceptual Design Reviews (NCSX, May 23, 2002; QPS, June 23, 2003).

Our stellarator theory research benefits from and heavily relies upon collaborations with researchers both at other labs in the U.S. program and within the international fusion program. Results of these collaborations will be discussed in more detail in the following sections. Some of the individuals we work with and the topics of collaboration are summarized in the following table.

Collaborators	Institutions	Topics of collaboration
Andrew Ware	University of Montana	Ballooning, global MHD, visualization
Raul Sanchéz	Universidad Carlos III de Madrid and CIEMAT	Ballooning, global MHD, Alfvén modes
Victor Tribaldos	CIEMAT	Neoclassical transport
E. Lazarus L. Lao	General Atomics	V3FIT 3D reconstruction code
J. Hanson Steve Knowlton	Auburn	V3FIT 3D reconstruction code
M. Isobe A. Shimizu	National Institute for Fusion Science (NIFS), Toki, Japan	Monte Carlo beam heating studies in CHS and CHS-qa, coil design for CHS-qa
D. Mikkelsen D. A. Monticello	Princeton Plasma Physics Laboratory	Transport modeling, PIES magnetic surface q uality calculations
L. Garicia	Universidad Carlos III de Madrid	MHD
K. Ichiguchi N. Nakajima	NIFS and University of Kyoto, Japan	MHD (Mercier stability, self-organized pressure profiles)
A. Weller A. Werner	Institüt für Plasmaphysics, Greifswald, Germany	MHD ballooning stability, Alfvén modes
H. Maassberg C. Beidler	Institüt für Plasmaphysics, Greifswald, Germany	Neoclassical transport in 3D systems

2.3.2 Recent Progress

2.3.2.1 Stellarator Equilibrium and Equilibrium Reconstruction

Both stellarator physics calculations and optimizations rely on accurate three-dimensional equilibria. Rapid calculation of these equilibria is also important for optimization studies. The VMEC code remains the premier tool for meeting these requirements; it continues to be the starting point for our physics and flexibility studies. It is also extensively used at stellarator laboratories worldwide. During the past year, significant improvements have been made in the speed and convergence properties of VMEC. By implementing a new preconditioner, it has become possible to reduce the MHD force residuals (errors in solving the partial differential equations) down to machine precision levels while maintaining short runtimes or runtimes comparable to previous (less well-converged) runs.

VMEC has also continued to play an important and unique role in the physics analysis of tokamaks. VMEC has been extended recently to include equilibria that violate stellarator symmetry. While this has not had any immediate applications to stellarators, it has allowed equilibria to be generated for tokamaks that do not possess vertical symmetry (such as occur in DIII-D and will be present in ITER). This has been augmented by a new Motional Stark Effect (MSE) diagnostic code that can now be applied to tokamaks with up-down asymmetries, such as occur with single-null divertors. A fast, reliable mapping code from real space coordinates to VMEC flux coordinates was developed in support of the MSE diagnostics applications of VMEC. In addition, this code is useful in adapting the AORSA rf heating code to three-dimensional configurations. VMEC has also been the only equilibrium code capable of treating the tokamak equilibria with current holes, which have recently become of interest for advanced tokamak scenarios. All previous tokamak equilibrium codes have been based upon the use of poloidal magnetic flux as a coordinate or independent variable; inside a current hole region, poloidal flux goes to zero and is no longer useful as a coordinate. VMEC uses the toroidal magnetic flux as a coordinate; since toroidal flux remains finite within a current hole, such equilibria can be readily calculated by VMEC. We expect that VMEC will continue to play an important role in the modeling and diagnosis of large tokamaks such as DIII-D and for future work relevant to ITER.

The intrinsic 3D nature of the stellarator equilibrium requires that the pressure profiles have zero gradient in each flux surface. We have continued to investigate the self-organization process that leads to such equilibria and the impact on ideal MHD stability. In collaboration with K. Ichiguchi of NIFS (National Institute for Fusion Science), we have investigated the evolution of the pressure profile as beta increases through a sequence of nonlinear calculations of resistive interchange instabilities that lead to equilibrium pressure profiles with saturated fluctuations [4,5]. We have started an evaluation of the effects of shear flows during such processes [6].

A second line of research that relates to self-consistent profile evolution, is the exploration of the self-similarity properties of the fluctuations in stellarators and the comparison with other devices. We have recently introduced a new technique of analysis, the quiet-times distribution than can shed new light on the fluctuation dynamics and its possible SOC character. We have applied this technique to the analysis of fluctuations in TJ-II and W-VII AS stellarators and showed that in both long-range correlations exist, which are very similar to the ones observed in tokamaks [7].

The next generation of compact stellarator hybrids (QPS, NCSX, CTH) will rely to a much greater degree on equilibrium reconstruction than existing large-aspect-ratio experiments. Both QPS and NCSX utilize three-dimensional shaping to achieve desirable confinement and stability properties; however, each will typically operate with time-varying plasma currents and plasma pressure, both of which result in changes to the plasma boundary shape and, consequently, affect the stability and transport of the plasma. In order to diagnose and control these effects in real time, an effort is under way to develop an equilibrium reconstruction code (V3FIT) which will interface to stellarator data acquisition systems and enable magnetic diagnostic design and flux surface reconstruction capabilities for 3D plasmas similar to those that the EFIT code provides for tokamak plasma experiments. This work has been carried out as a joint project between ORNL, GA, and Auburn. As β rises in low-aspect-ratio hybrid stellarator configurations with net plasma current, such as the NCSX, QPS and CTH experiments, this capability becomes increasingly important for accurate equilibrium analysis and plasma control.

A test-bed version of V3FIT uses similar optimization techniques to determine the equilibrium that provides the best fit to a set of flux loop measurements as the STELLOPT code used to determine the equilibrium that provided the best minimization of a set of physics criteria. The concept of reciprocity is used to calculate the responses of the diagnostic magnetic loops. When this method is used, the response matrix for each diagnostic coil can be stored in a database once and reused during the equilibrium reconstruction. During the past year an extensive paper has been written [8] that describes the capabilities of V3FIT. Also, a long-standing problem with the calculation of magnetic fields using the Biot-Savart law near current line segments was analytically resolved [9], leading to a faster Biot-Savart numerical solver. In addition to stellarator applications, V3FIT is expected to offer new capabilities for tokamak reconstruction such as better diagnosis of up-down asymmetric equilibria, and potentially inclusion of nonaxisymmetric effects such as internal MHD phenomena (sawteeth, neoclassical tearing modes), non-symmetric wall structures, and TF ripple. V3FIT is being developed so that it may use more realistic (islated) equilibria in the future.

2.3.2.2 Stellarator Transport and Confinement

Confinement improvement at low reactor-relevant collisionalities has been a central goal of both QPS and NCSX compact stellarator optimization studies from the beginning of these efforts. The understanding and validation of this transport optimization in future experiments will require ongoing development of a number of theoretical and modeling tools. This effort has been started, but, as these are generally long lead-time projects, the work will be ongoing through the experimental operation phase. An important issue for experiments will be their capability to generate the sheared flows and electric fields required for access to enhanced confinement regimes. Since plasma flow damping is a function of the magnetic field structure, it is expected that stellarators with different quasi-symmetries (QP, QA, QH) will have different characteristics in this respect. In order to address this, one of our accomplishments during the past year has been to adapt a recently developed fluid moments method for stellarators to our equilibrium and transport coefficient codes. We have also continued to evaluate the transport characteristics (e.g., energy lifetimes, temperatures) of QPS configurations in support of the Conceptual Design Review that occurred in June 2003.

Our most basic level of transport analysis has been through the use of either 0-D or 1-1/2D models that are based on transport coefficients that include both asymptotic neoclassical results and anomalous components. The neoclassical coefficients are typically based upon results for the effective ripple obtained from the NEO code combined with the constrained helicity model of Shaing and Houlberg for the ambipolar electric field dependence. This model has been developed by D. Mikkelson and M. Zarnstorff of Princeton Plasma Physics Lab. and applied to our QPS configurations. Such calculations have been very useful for answering issues such as what degree of optimization is required to make neoclassical losses subdominant to anomalous losses, and how much heating power is required to reach levels of plasma β that allow tests of ballooning stability limits.

The next level of description is the kinetic calculation using the Drift Kinetic Equation Solver (DKES) of the neoclassical coefficient matrix for arbitrary collisionalities and electric field levels, taking into account multiple helicities in the magnetic field spectrum. An important extension to this work was made during the past year [10], allowing the calculation of viscosities (see Fig. 2.23) and flows in three-dimensional systems based on a fluid moments method. This approach takes into account momentum conservation between species and can provide a more self–consistent set of transport coefficients for the 1-1/2 D calculations. It also will allow calculation of the profiles of poloidal and toroidal flow velocity components.

Since multiple ion species can be included, this method can be extended to study impurity flows and accumulation. During the past year, computational tools were constructed to run DKES over a range of flux surfaces, collisionalities and electric field values; the flux surface loop is generally done using parallel computing techniques. These monoenergetic results are then collected together in a database and augmented with respect to collisionality using analytically derived dependencies to cover necessary ranges of collisionality where DKES cannot provide converged results. These transport coefficients were then combined using results of Sugama, et al. [11] and appropriate energy integrations performed to obtain the viscosity coefficient tensor.

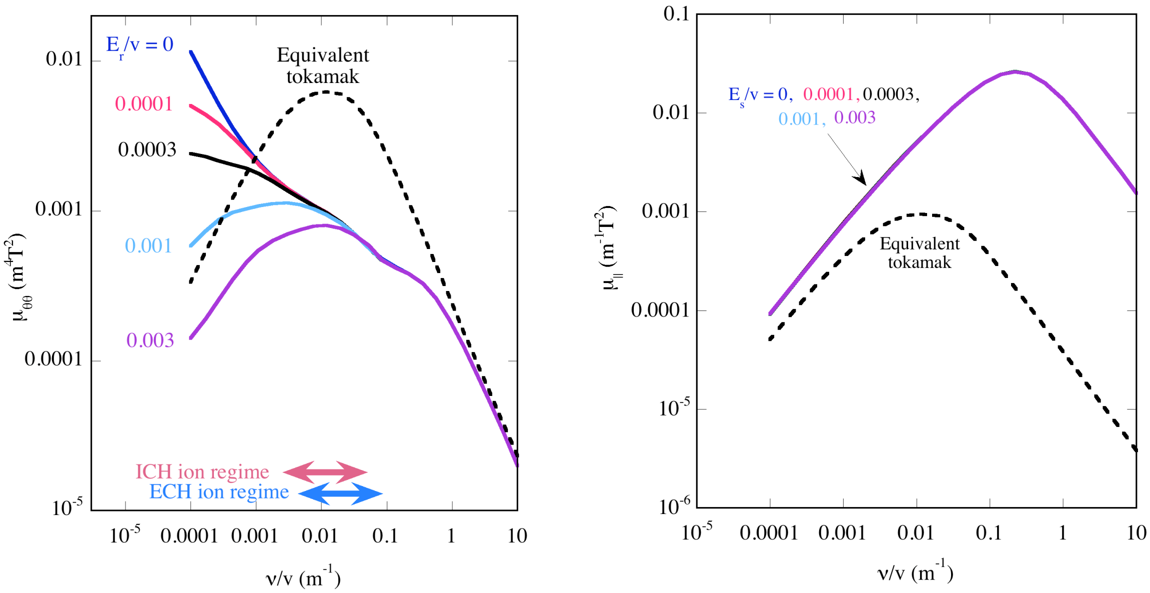


Fig. 2.23. Monoenergetic poloidal (left-hand plot) and parallel (right-hand plot) viscosity coefficients for QPS and the equivalent tokamak configuration vs electric field and collisionality parameters.

Also, the coupled ion/electron particle and energy flows and bootstrap currents have been calculated. Ambipolarity conditions based on these calculations have been checked for axisymmetric devices and against previous results (based direct integration of the DKES coefficients) for stellarator configurations. This work will continue and comparisons will be made between different configurations. Since one of the possible advantages of quasi–poloidal symmetry is a lower threshold for driving the poloidal flows and sheared electric field profiles that can suppress turbulence, analyzing viscosities in such configurations is an important issue. The results so far have indicated that poloidal viscosities in a QPS device are suppressed (by about a factor of 10) from what they would be in an equivalent tokamak configuration.

The third transport model we utilize is the particle-based Monte Carlo approach (DELTA5D code). This allows one to include higher-dimensionality effects such as large orbit deviations from flux surfaces and energy scattering. Such models have been used to obtain global energy and particle lifetimes for different QPS configurations. These have been especially useful in testing varying coil-current flexibility studies of QPS that target simpler transport measures such as low collisionality transport and the degree of quasi-poloidal symmetry. Monte Carlo studies have indicated that trends based on these target functions sometimes times reverse when global confinement times in more collisional regimes are calculated. Extensive studies of this type were done in support of the QPS Conceptual Design review in June 2003. The DELTA5D Monte Carlo code has also been used to assess the confinement of energetic ion components. For example, neutral beam losses during slowing-down in NCSX [12], interpretations of charge exchange diagnostics in LHD [13] and alpha slowing down losses in QPS reactor scale devices have been calculated. We also collaborate with M. Isobe of NIFS on the topic of neutral beam losses in the CHS and CHS-qa devices.

The DELTA5D code was also adapted to follow relativistic runaway electron populations (as might be produced by Ohmic heating or turn on of modular magnet coils) and enhanced electron tail populations (as might be produced by ECH). This was initially motivated by a need to assess runaway loss locations in QPS relative to the plasma-facing coil casings; however, there is also interest in the possibility of generating runaways in stellarators in a more controlled way and using their loss characteristics as a way to diagnose plasma micro-turbulence levels. Such techniques have been used previously on the ASDEX tokamak to infer anomalous transport levels [14].. It is expected that currentless stellarators could offer a more quiescent environment for such studies. Interest has been expressed by the TJ-II group (CIEMAT, Spain) in working with us on this area.

2.3.2.3 Stellarator MHD Stability

MHD stability theory for compact stellarators has focused both on localized Mercier and high-n ballooning modes as well as finite-n kink and vertical modes. In addition, we have started to analyze energetic particle destabilized Alfvén modes in 3D systems.

Our work on ballooning instabilities continues to rely on the COBRA code, which is now based on VMEC equilibrium coordinates and provides very rapid yet accurate evaluations of ballooning growth rates. This calculation is routinely used in our stellarator optimization code STELLOPT to restrict our searches to stable devices and profiles. It is also used in a postprocessing sense to carry out flexibility studies and determinations of the marginally stable plasma β. For our reference QPS configuration, extensive flexibility studies were carried out for the Conceptual Design Review in which coil currents and plasma current profiles were changed. It was determined that a range of modular coil current variations can make ballooning modes unstable for the moderate β's ($1.5\% < \beta < 2\%$) that should be attainable in a QPS experiment. Also, Ohmic-driven current profiles tend to lower ballooning thresholds below those obtained for bootstrap consistent profiles.

MHD ballooning stability has also played a central role in the development of new QPS reactor configurations. We have found a range of devices that can access second stability and achieve β's of ~15%, which are the highest ballooning limits ever predicted for a stellarator. These systems are also competitive with advanced tokamaks since they are second ballooning stable at much lower levels of self-generated bootstrap current than is the case for the equivalent tokamak device. This leads to a much higher Tryon factor ($\beta_N = 19$) than can be achieved in an equivalent tokamak ($\beta_N \sim 3$) with no wall stabilization [β_N is defined as: $\beta(\%)$ <a(m)> B(T) /I(MA)]. Results for these configurations have been published [15].

In addition to ballooning stability, low-n stability calculations have been carried out for the QPS device by A. Ware using the TERPSICHORE code. Kink and vertical displacement modes have been examined for a free boundary model. In general, the plasma pressure thresholds are significantly higher (β = 4 to 5%) than those for ballooning instabilities ($\beta \sim 2\%$). We have recently been provided with the source code for TERPSICHORE by Anthony Cooper of Lausanne and have been able to successfully install and run it on our Linux workstations. It expected that at some point in the future we will include this as a new physics target function in the STELLOPT code.

We have also analyzed Alfvén mode continuum structures and eigenmodes in 3D systems [16]. This work will form the basis for MHD spectroscopy studies and future efforts concerning the destabilization of these modes by energetic particle components. The STELLGAP code has been developed and applied to calculate the Alfvén continuum gap structure for a variety of existing and planned stellarators. This calculation uses parallelism to improve performance and to allow high resolution in the mode spectrum and radial structure. A study has been carried out for a range of different stellarators: W7-AS, W7-X, LHD, CHS, QPS, NCSX [16]. indicating that while the stellarator–specific helical Alfvén gaps are generally present in all devices, they are present at lower frequencies and closer to the magnetic axis in the low-aspect-ratio systems than in the higher-aspect-ratio systems (see Fig. 2.24). Also, the low-aspect-ratio systems have larger open gap structures at low frequencies than the high-aspect-ratio configurations. This fact could imply that a larger number of discrete modes may be present for destabilization. We have also developed a separate code for calculation of the Alfvén eigenmodes that are present within the continuum gaps; modifications are currently under way to improve the accuracy and speed of this code. Interest in applications of these codes have been expressed by U. Stroth for the TJ-K stellarator where experiments are planned to excite Alfvén eigenmodes using plasma probes and by David Brower of the HSX experiment, where Alfvén modes excited by ECH electron tail populations may have been observed. Initial calculations have already been carried out for both devices. Collaboration continues in this area with A. Weller and A. Werner of the IPP-Greifswald concerning data from the W7-AS device [17]. Also, recent interest has been expressed by the TJ-II group (CIEMAT, Spain) where neutral beam-driven Alfvén modes have been measured; calculations using STELLGAP have been initiated for this device.

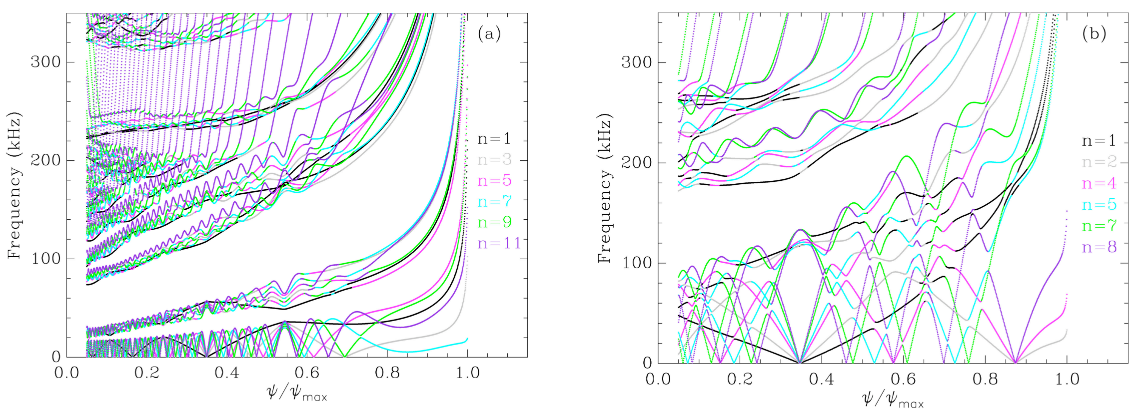
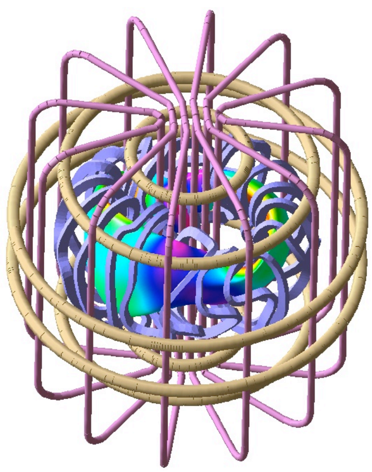


Fig. 2.24. Alfvén gap structure for n = 1 mode families in QPS (left-hand plot) and NCSX (right-hand plot).

2.3.2.4 Stellarator Flexibility Studies and Island Suppression

ORNL has been a leader in the development of coils and optimized configurations for both the NCSX and QPS stellarator programs. As these designs have become fixed, our optimization interests have shifted toward flexibility studies and techniques for island suppression in the presence of error fields. Recently developed stellarator computational design tools (the STELLOPT code) have successfully merged the optimizations of external coils for engineering and internal plasma physics. This procedure allows one to methodically explore the physics flexibility options in a completed design where the coil geometry is fixed but where the coil currents can still be varied over some specified range. This type of flexibility is one of the significant advantages that stellarators can offer that tokamaks cannot. Developing better tools for exploring the available parameter space can also significantly enhance the scientific value of a stellarator experiment.

During the past year, we have applied these methods for flexibility analysis to the QPS design. This device will offer independent control over three vertical field coil currents, one toroidal field current and five modular coil currents (see Fig. 2.25). Including the plasma current, this results in ten parameters can that can be independently controlled. Since searches of even a ten-dimensional parameter space, based on intuition or trial and error, are likely to miss interesting combinations, we have used the merged coil–plasma optimizer code STELLOPT to automate this search process. So far we have focused on using these currents to both improve and degrade low collisionality transport and to suppress vacuum magnetic islands. With respect to transport, about a factor of 25 variation can be made in low collisionality transport levels (see Fig. 2.25), as measured by the effective ripple coefficient. At the more moderate collisionalities that will characterize the experiment, this translates into about a factor of 10 variation, as measured by DKES calculations and Monte Carlo lifetimes. Using the recently developed poloidal viscosity calculation, this also results in about a factor of 10 variation in viscous damping.



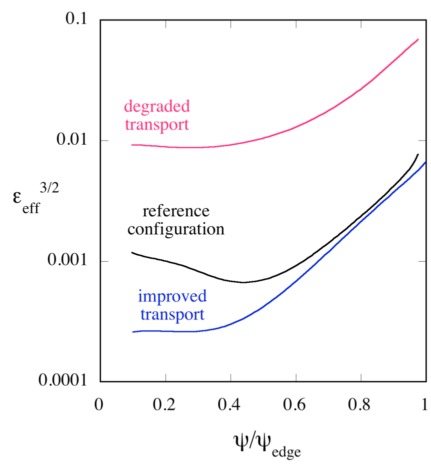


Fig. 2.25. QPS coil systems (left) and flexibility studies of the effective ripple (proportional to low collisionality transport) vs flux surface location (right).

With respect to magnetic island suppression, two methods have been used. First, the islands have been directly targeted using the residuals approach that was developed earlier by Cary and Hanson [18]. This has been successfully applied toward the reduction of vacuum island widths (see Fig. 2.26).

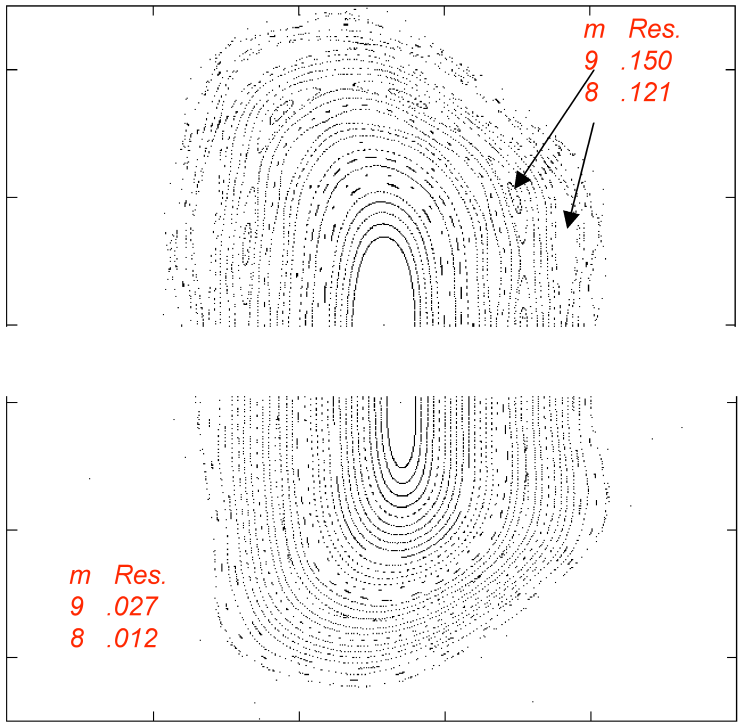


Fig. 2.26. Suppression of QPS vacuum islands using residue targeting. Upper: QPS vacuum field, reference coil currents. Lower: Final state with residues minimized

Second, the approach that has been successfully used in the Wendelstein experiments (maintaining the rotational transform profile between adjacent low order rational values) has been implemented by varying both the plasma current level (assuming an Ohmic heating profile) and the coil currents. This approach has been used successfully both for vacuum and finite plasma pressure equilibria. It is expected that a range of island-suppressed windows for rotational transform profiles will exist between the 2/8, 2/7, 2/6 and 2/5 resonances. These techniques should allow both good vacuum field configurations to be found as well as startup scenarios for rising plasma current and pressure. Eventually, the compatibility of the coil current programming used for these flexibility studies with the requirements for the Ohmic current drive system will also need to be addressed.

The STELLOPT/COILOPT suite of codes continues to be maintained and adapted to run on a wide range of computing platforms. It efficiently uses parallelism to achieve high performance on computing platforms such as the Seaborg system at NERSC and the Eagle and Cheetah systems at ORNL. It also can be run on local Linux, IBM-PC, and Macintosh OS X workstations. STELLOPT/COILOPT codes now use the platform-independent netcdf binary file format for their output files.

2.3.3 Proposed Research

2.3.3.1 Stellarator Equilibrium

As mentioned earlier, the next generation of compact stellarator hybrids (QPS, NCSX, CTH) will require good equilibrium reconstruction both for diagnostics and external control of the plasma position and shape. An effort is underway to develop an equilibrium reconstruction code (V3FIT) that will interface to stellarator data acquisition systems. The goal is to enable magnetic diagnostic design and flux surface reconstruction capabilities for 3D plasmas similar to those that the EFIT code provides for tokamak plasma experiments. The next major project in this area will be to develop efficient algorithms for computing diagnostic signal gradients with respect to pressure and current profile coefficients. This is challenging in 3D because the magnetic differential equation for the parallel current cannot in general be solved analytically, as it can in 2-D systems with symmetry. Applications of V3FIT to existing (LHD, CHS) experiments will be explored. Also, a trial set of NCSX magnetic sensors will be modeled and tested with V3FIT

A number of improvements will be made in the computational efficiency of the code that follows magnetic field lines to allow more rapid assessments of the flux surface fragility of low-aspect-ratio stellarators. In addition, this code will be used to analyze error fields in the QPS and NCSX designs due to various types of coil misalignments and manufacturing errors.

An entirely new approach to 3D equilibria has been formulated based on a pair of stream functions. The new approach would greatly improve the convergence and resolution of the inverse equilibrium solvers. However, progress in this direction will depend on additional funding and/or development of collaborative contacts with researchers at outside institutions.

2.3.3.2 Stellarator Transport and Confinement

The existing set of stellarator transport computational tools (1-1/2D model, DKES, Monte Carlo) will continue to be used to evaluate the transport properties of the QPS design. Now that the designs for QPS and NCSX are fixed, it is expected that these tools will be developed in more depth than had previously been possible. Also, flexibility studies for QPS will continue in order to explore the range of transport levels that can be achieved through coil current variations. There are several new transport-related optimization targets, such as poloidal/parallel viscous damping, collisional bootstrap current, and plateau transport, that could be added to the flexibility target functions.

In the area of 1-1/2D transport modeling (done in collaboration with D. Mikkelesen at PPPL), we plan on replacing the asymptotic and limited helicity neoclassical transport model that is currently being used in the 1-1/2D model with particle and energy fluxes obtained from the DKES-based fluid moments method. A set of codes for computing the required DKES coefficients have been installed on the Linux cluster at PPPL and benchmarked against other computers. This consists of a primary code that runs multiple DKES calculations in parallel, assigning processors to different flux surfaces, cycling through loops over collisionality and electric field for each surface, matching to asymptotic forms when the collisionality is too low for DKES to converge, and finally carrying out the energy integrations and necessary calculations to obtain the transport fluxes. Although these codes are all functioning, they haven't yet been merged with the 1-1/2 D transport model. Work should continue on this during the coming year. In addition to the above transport model, we will also continue working with outside groups (IPP-Greifswald, PPPL, CIEMAT, NIFS) towards the development of a comprehensive predictive/interpretive transport code for stellarators.

Further development of the local DKES transport coefficient model will continue based on the analysis of Sugama and Nishimura [11]. It will provide a technique for modification of the DKES coefficients to incorporate momentum conservation and obtain the neoclassical viscosity tensor components. Also, predictions of collisional bootstrap current effects and more consistent solutions for the ambipolar electric field for both QPS and NCSX devices will be obtained. These will be compared with earlier solutions based on direct use of the DKES transport coefficients without momentum conserving effects. The evaluation of flow velocities should allow assessments of the extent to which either driven or self-generated sheared flows can suppress turbulence in these devices. We expect to evaluate flow velocity characteristics for stellarators with the three main types of quasi-symmetry (i.e., helical, poloidal, toroidal).Work will be started on the topic of including impurity species in the transport model. The issues of impurity accumulation and methods of influencing the direction of impurity flows in QPS will be of long-term importance.

The above transport analysis topics depend on the existence of accurate, rapidly evaluated neoclassical transport coefficients over wide ranges of collisionality and electric field. Although the DKES code can fulfill a significant part of this need, it has convergence difficulties (i.e., requires progressively higher resolution and longer running times) at low collisionality and is limited by the physics model used at high electric fields and collisionalities. A number of options for treating these more extreme parameter ranges will be explored. One option is to use delta-f Monte Carlo techniques. This has been successfully demonstrated with the MOCA code for the D_{11} transport coefficient [19] but not for the D_{31} bootstrap current coefficient, which is required in the momentum-conserving fluid moments approach. Another choice is to apply boundary layer solution techniques to numerically calculated stellarator transitional boundary regions. Finally, upgrades to the DKES code to include higher dimensionality (by adding either energy or radial variation) are under consideration. This can allow better treatment of the high electric field/collisionality regime and also possibly improve the low collisionality convergence (i.e., by adding dimensionality the boundary layers should spread out somewhat). We expect to pursue all three of the above choices to some extent and to identify which choice emerges as the best option.

In the area of particle-based Monte Carlo analysis of transport, we expect first to continue our efforts on particular topics where this approach can have near-term impacts. These include neutral beam and alpha particle slowing-down calculations, delta-f based models of bootstrap current, the use of electron beam orbit trajectories at low magnetic fields (e.g. ~100 Gauss) to probe QPS magnetic field optimization, and runaway electron damage patterns on coil casings. In addition, we expect to develop a code that will follow ensembles of orbits in magnetic fields (that contain islands) obtained directly from coils. There also remain a number of issues that we would like to address with Monte Carlo that have tended to be too computationally expensive to fully develop. These include maintenance of self-consistency between the initially assumed background density and temperature profiles and those of the evolving test particle distribution, calculation of the ambipolar radial component of electric field through balancing the ion and electron fluxes, calculation of the variation of the ambipolar potential within a flux surface through invoking quasi-neutrality, and slow approach to neoclassical equilibrium at low collisionality and for larger devices. Methods will be explored to achieve higher performance in the Monte Carlo model so that it will become feasible to address these issues.

An alternate approach to full Monte Carlo simulations is the use of recently developed nonlinear dynamics methods to characterize the transport phenomena measured in the simulations. This would be based on the hope that, at least to some degree, universal scaling behavior emerges. For example, transport equations involving fractional derivatives or nonlocal integral kernels may provide useful ways to model nondiffusive transport. We will apply such techniques to results from our stellarator Monte Carlo particle simulations of both energetic tail plasma components and to plasmas with broken magnetic surfaces. If successful, this could lead to new forms of reduced transport equations that could describe nondiffusive behavior in a more flexible and rapidly evaluated way than running direct Monte Carlo simulations. Such methode can also be employed to study transport in Monte Carlo models that include both static and fluctuating (instability induced) background fields.

2.3.3.3 Stellarator Stability and Turbulence

Stability analyses of QPS configurations will continue based upon the COBRA code for ballooning instabilities and the TERPSICHORE code for lower-n global modes. Although further development of COBRA is not foreseen, it is expected to play a central role in flexibility studies that will be undertaken to find ways to test ballooning stability limits in a future QPS experiment. We also plan to use COBRA to examine the effects of introducing the lowest order ion FLR (i.e., ion diagmagnetic drifts) into the ballooning calculation using techniques developed by J. G. Wohlbier and C. Hegna of the University of Wisconsin. This will require running COBRA over a range of field lines, flux surfaces, and starting positions and then assembling the global eigenfunction from the data using WKB ray-tracing methods. Such calculations should be well adapted to parallel computers. Inclusion of FLR should allow a prediction of the maximum toroidal mode number that needs to be considered with respect to ballooning stability boundaries. Based on the impact of ion FLR on tokamak ballooning boundaries, it may also be expected that these effects will aid in opening up a stable path for access to second stability. The TERPSICHORE free-boundary variational code (working in collaboration with Andrew Ware of the University of Montana and G-Y. Fu at PPPL) will be adapted to the boundary shape of the QPS design so that it can be more routinely used in evaluating kink and vertical displacement stability thresholds. At some point, it should also be possible to include TERPSICHORE in the suite of optimization targets of STELLOPT. This would allow flexibility studies of kink and vertical mode stability.

Discussions have started with G-Y. Fu (PPPL), Linda Sugiyama (MIT) and Hank Strauss (NYU) with respect to the application of the M3D nonlinear MHD code to QPS. This will be pursued during the coming year; if possible, it would allow studies of low-n resistive and two-fluid instabilities in QPS. A further instability that needs to be analyzed in low-aspect-ratio stellarators is the neoclassical tearing mode. Although QPS and NCSX are designed with stellarator-like shear (stable to neoclassical tearing modes) in their nominal state, flexibility studies will likely drive both devices into regimes where tokamak-like shear profiles are produced that will be unstable to neoclassical tearing modes. Methods for analyzing these modes in three-dimensional systems will be explored.

We will continue the exploration of a stable path to high beta by sequential nonlinear resistive stability calculations and comparison with the LHD experimental results. Emphasis will be given to the role of self-generated flows in developing such path. To carry out this research, we will continue the collaboration with the theory group at NIFS. We also plan to continue the investigation of the fluctuation properties in stellarators and comparison with tokamaks. Some of the present studies will be extended to plasma core fluctuations.

Further work will be done in the area of fast-ion-destabilized Alfvén modes in 3D systems. The calculation of the discrete Alfvén eigenmode structure will be improved. This code will be developed as a tool both for use in MHD spectroscopy studies (i.e., excitation of Alfvén modes via antennas or probes) as well as for studies of stability. Collaborations in this area have been started with a number of experiments: TJ-K (Uli Stroth), TJ-II (Raul Sanchez), HSX (David Brower), and W7-AS (Arthur Weller). Adaptation of this code to a free boundary model may become necessary on the longer term for MHD spectroscopy applications. Several approaches are under consideration for Alfvén stability calculations, including energy principles and time evolution models. An ultimate goal would also be to be able to do nonlinear simulations. Efforts will be made to improve the performance of the existing Alfvén continuum calculation so that it could be usable as an optimization target.

2.3.3.4 Stellarator Optimization and Coil Design

Our optimization and coil design efforts will be continued with the primary applications being QPS flexibility and island suppression studies. As mentioned in the technical progress section, good success has been achieved with use of the STELLOPT code to scope out the possible ranges for physics flexibility for QPS. This effort will be continued and additional target functions, such as poloidal viscosity and improved QP-symmetry may be tried. The transport flexibility studies have so far only been done for vacuum equilibria; these will eventually need to be extended to finite beta and made consistent with stability flexibility studies.

Island suppression studies have also been initiated during the past year and will be continued. These calculations are motivated both by the need to minimize vacuum islands (e.g., as caused by small coil misalignments and other field errors) as well as the avoidance of islands as the plasma β, currents and profiles change in time. The dynamical nature of coil current programming for low-aspect-ratio hybrid stellarators (with time-varying currents) is a new and challenging problem that will need to be addressed before experiments come on line.

Vacuum islands have been minimized both by keeping the rotational transform away from low order rational values, as well as targeting functions that more directly reduce island width. The latter target functions seek to maximize the region containing integrable flux surfaces, and reduce the volume occupied by magnetic islands. Methods based on minimizing the residues of low-order fixed points in 3D magnetic fields with rotational transform have proven to be effective in achieving this goal. Important near-term applications include the possibility of optimizing the alignment of manufactured modular coils to minimize the impact of vacuum magnetic islands in the NCSX and QPS designs. The same analysis could provide an additional figure-of-merit in the design optimization of modular coil shapes for compact stellarators. Methods that keep the rotational transform away from low order rational values can be applied both to vacuum and finite pressure equilibria. These calculations have so far identified a few isolated windows of operation (between the 2/6 and 2/7 resonances for vacuum and between the 2/5 and 2/6 resonances at 2% beta) were islands can be avoided. It will be of interest to extend this technique to identify other windows of operation for QPS.

In addition to the near-term QPS device, reactor studies have recently been initiated for compact stellarators. We expect to work on several new optimization target functions for these studies. In the area of energetic particle confinement, we will try a more specific approach of looking only at particles launched near the trapped-passing transition region. Past experience with Monte Carlo calculations has shown that this group tends to have the highest losses. In order to do optimizations with a discretely varying target function such as this, it will be necessary to rely either on nonderivative based methods (differential evolution or genetic algorithm) or to do some type of averaging over multiple optimization cycles. Also, as mentioned in the previous section we will study ways to introduce target functions for Alfvén instabilities.

2.3.3.5 Stellarator rf Heating

Due to the fact that QPS relies solely upon rf heating, more calculations in this area will need to be carried out. The high density phase of the QPS experiment depends on the success of either HHFW or EBW heating techniques. More analysis and modeling will need to be pursued for these heating methods.

Full wave calculations have been done with the AORSA code for the LHD stellarator. As a result of recent improvements in the efficiency of AORSA, this code can now also be applied to QPS. This work will continue, but due to its very computationally intensive nature, it will likely be applied in only to a limited number of cases.

2.3.3.6 Stellarator Edge Physics

Edge physics studies of stellarators will be continued to address divertor/baffle design, armor plate location for intercepting particle losses, and open field line connectivity to edge regions. A specific issue that was mentioned earlier is the calculation of likely loss regions for energetic runaway electrons as may be produced by the initial ramp-up of the modular field coil currents or by the ECH heating. This has been evaluated with our existing closed magnetic surface model, but we would like to extend this to include edge regions with magnetic islands and stochastic field line regions.

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