Input from the US Stellarator Research Community to the FESAC Panel on Toroidal Alternates

June 2008

Abstract

International research carried out over the past 5 decades has steadily validated the ability of the stellarator magnetic configuration to confine high performance, macroscopically quiescent plasmas with inherent steady-state capability. Sharing many of the same physics characteristics as tokamaks, stellarators attain similar plasma parameters and figures of merit to comparably-sized tokamaks. In conjunction with ongoing tokamak research in the burning plasma era, work on stellarators over the next twenty years is intended to develop the stellarator concept to be ready to proceed to a DEMO-scale experiment. Apart from the plasma-wall interaction and materials problems that confront all steady-state toroidal reactor concepts, the stellarator does not exhibit a clear scientific 'show-stopper' that would preclude it from successfully confining a burning DT plasma. The main challenges confronting the stellarator concept specifically are to validate that our understanding of 3D plasma confinement physics extends to fusion relevant plasma parameters and to systematically develop system designs that accommodate the complexity of the highly-shaped, three-dimensional plasma configuration and the magnet coils that produce it. The progress of the stellarator toward its DEMO goal will be facilitated to a great extent if the stellarator coils can be simplified while still producing the magnetic configuration required for good confinement, stability, and fusion gain. To do so will require improved understanding of the behavior of existing and future stellarator plasmas coupled with the ability to provide the necessary shaping of the 3-D magnetic flux surfaces with an efficiently-engineered set of coils.

Prologue

As this report was being prepared, the US stellarator program suffered a significant setback with the termination of NCSX. The worldwide program is engaged in showing the tremendous opportunities available through stellarator optimization for steady-state, disruption-free operation. Stellarator performance extension devices exist (LHD) or are under construction (W7-X). Quasi-symmetric systems that permit some toroidal current and low flow damping are presently only investigated at the CE level and in the US. Despite the loss of NCSX, the physics opportunities for stellarators remain clear and compelling.

Fifty years of successful stellarator experiments and theory have brought the program to the high level of performance it exhibits today. W7-X and NCSX are first-of-a-kind devices in this succession. While they represent large steps from state-of-the-art experience, both are now meeting their technical requirements. With regard to NCSX, however, DOE Undersecretary of Science Orbach stated, "An Office of Science review (April 2008) concluded the project has not yet met the requirements needed to approve a new baseline cost and schedule." Specifically there are elements of the design not completed. That said, the coils are almost finished and within specification. It is clear, however, that the stellarator would benefit greatly from more tractable engineering coil designs and tolerance specifications; these elements are discussed in this report as an opportunity.

The cancellation of NCSX leaves a large gap in assessment of the correct next step for the overall stellarator concept. We will need a quasi-symmetric PoP, at a minimum, to correctly decide this step. How this should proceed is, at the moment, an open question requiring resolution. It is clear that the strategic planning process should begin now to fill this gap in the international program. The US has taken leadership in quasi-symmetric stellarators, and this opportunity cannot be allowed to lapse.

I. Goals

The ultimate aim of stellarator research is the reliable and continuous generation of electric power at industrial levels in a manner that is both environmentally benign and cost-competitive with other power-producing technologies of the future. During the next two decades, it is expected that results from burning plasmas in ITER will inform critical decisions on the nature of DEMO, the next major and penultimate step to fusion power production for the public. The ITER research plan and the subsequent transition to DEMO motivate strategic planning of stellarator research in the run-up to the time when results from DT-burning plasmas will be available. With this in mind, the primary goal of stellarator research in the next 20 years is to:

> **develop the scientific and technical basis for using stellarator configurations for steady-state fusion energy production.**

Through experiments and modeling performed on both stellarators and tokamaks (including ITER), stellarator researchers plan to develop the level of predictive understanding in concert with the attainment of sufficiently promising plasma conditions that would justify the step to implementing a fully steady-state, disruption-free, externally-controlled, DT-burning stellarator as the forerunner to a toroidal fusion power plant.

A stellarator confines a high-temperature plasma in a toroidal magnetic configuration in which controlled currents in external coils produce vacuum flux surfaces with rotational transform. In this regard, it is clearly distinguished from tokamaks and other toroidal concepts that rely primarily on current flowing through the conducting plasma for confinement. While the magnetic geometry of most toroidal confinement systems is intended to be entirely symmetric in the toroidal coordinate, the magnetic field components of the stellarator configuration, by necessity, vary in all three coordinates to generate the nested magnetic flux surfaces required for plasma confinement in a toroidal system. Stellarators are thus 3-D devices in which the descriptive physics and fusion technology are fundamentally shaped by the non-symmetric character of their magnetic geometry. While all toroidal plasmas exhibit non-axisymmetric field perturbations that can have important consequences on their behavior, stellarators are **unique** in their dependence on fully three-dimensional fields for confinement. This fact motivates a secondary goal of stellarator research:

Contribute to the understanding of key science issues arising from three-dimensional effects in toroidal magnetic confinement configurations.

Within the context of fusion systems, non-symmetric fields allow for maximal external prescription of the plasma configuration and behavior, and so reduce the dependence on non-linear self-organization.

The most significant scientific weakness of the classical stellarator approach is the insufficient confinement of particles in the low collisionality regime, which would lead to an unacceptable level of prompt loss of fusion alpha particles. With the recognition that neoclassical transport in toroidal systems is determined by the configurational variation of only the magnitude of the magnetic field, stellarator systems have been designedsuch that |**B**| is symmetric within a flux surface in a particular coordinate to produce drift orbit trajectories that are, on average, aligned with the flux surfaces. The three general types of so-called quasi-symmetry that are possible in toroidal systems are quasi-helical (QH), quasi-axial (QA) and quasi-poloidal (QP). A similar optimization can produce a quasi-isodynamic configuration in which the net deviation of the particle drift surfaces from the magnetic flux surfaces is minimized. Quasi-symmetric optimization predictably provides good neoclassical confinement, and can reduce viscosity to levels comparable to that in tokamaks. The experimental implementation, testing, and further development of quasi-symmetric configurations, and 3-D shaping in general, are hallmarks of modern stellarator research and are also key thrusts of the US program. They figure strongly in many of the issues raised later in this document.

II. Merits of the stellarator approach to fusion

The helical stellarator configuration bears clear similarities to the tokamak. Equilibria of both stellarators and tokamaks are characterized by a strong toroidal field and comparable values of rotational transform. Measured global confinement times in stellarators follow a very similar scaling to those in tokamaks, as shown in Fig. 1, and project well to ITER. Steady state power & particle handling issues are about the same as for tokamaks. Much of the progress made in both theoretical understanding and experimental practice on tokamaks is directly applicable to stellarators, which thus benefit from the transport modeling, diagnostic and heating systems development, plasma-wall interaction studies, etc. addressed in high-performance tokamak plasma environments. These similarities guarantee that results from DT ITER plasmas coupled with validated modeling will provide essential knowledge of burning plasmas to fold into the design of a stellarator DEMO.

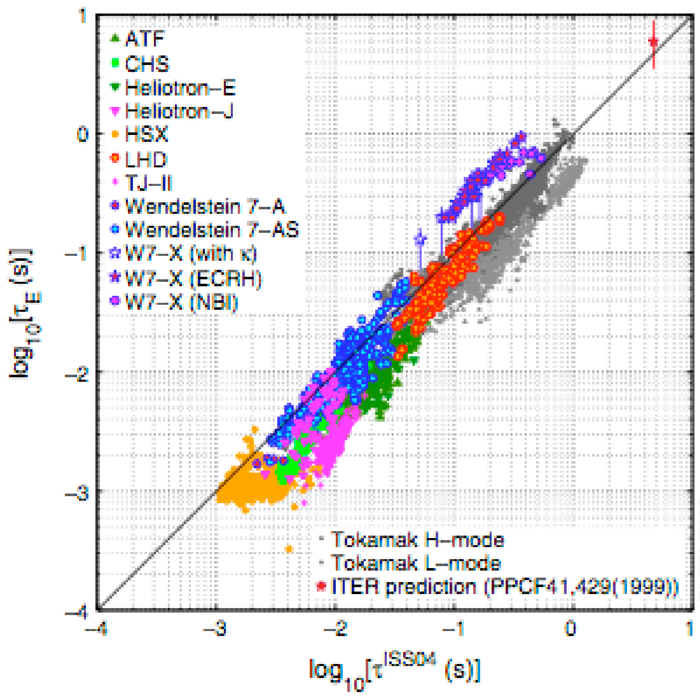

Fig. 1 Energy confinement time in various stellarators and tokamaks versus the ISS2004 stellarator confinement scaling law. Also shown are projected confinement times from W7-X and ITER. [From A. Dinklage et al, Nucl. Fusion **47** 1265 (2007)]

At the same time, stellarators possess a number of significant merits as toroidal fusion systems. These are:

A. **Intrinsic steady-state equilibrium**

With the equilibrium field configuration produced largely by currents in external coils, stellarators with superconducting magnets are capable of confining plasmas continuously. While bootstrap current will influence the rotational transform and may be used as an optimizing tool, it is not essential for steady-state operation; nor is auxiliary current drive with its associated penalties of cost, level of recirculating power, and issues of technical reliability, required for continuous discharges.

B. **Lack of major disruptions**

With limited plasma current, stellarator discharges with up to the highest attained values of $\langle\beta\rangle = 5\%$ do not exhibit serious “off-normal” terminations (disruptions) in which the energy content of the plasma is rapidly lost to the wall, divertor, and surrounding conducting structures.   Neither are resistive wall modes or vertical displacement events observed or a primary concern. As in other confinement devices, stellarator discharges can undergo radiative collapse due to high density and low input power, or the unexpected introduction of a flake of wall material, but the terminations are relatively benign; halo currents or runaway electrons that would threaten the wall are not generated. Furthermore, the radiative collapse in the stellarator occurs on a transport time scale, which is typically slower than events triggered by growing MHD instabilities in tokamaks.

C. Robust prescription of the magnetic equilibrium

The rotational transform profile in the stellarator is determined primarily by the currents in the external coils instead of by plasma currents. Improvements in transport and avoidance of instabilities can be achieved by passive adjustment of the magnetic configuration with the use of the poloidal field coils. There is little need envisioned for active control of the profiles that may be needed in more self-organized, nonlinearly-dependent toroidal configurations. Furthermore, neoclassical tearing modes are predicted and observed to be robustly stable in the rotational transform profile typical of stellarators.

D. High density operation feasible in stellarator.

High plasma densities comparable to those that can only be obtained in high-field tokamaks are achieved in stable stellarator discharges of moderate magnetic field strengths. The density of the stellarator plasma apparently is unconstrained by an equivalent Greenwald limit (when the plasma current in Greenwald's formulation is converted to rotational transform to enable comparison with stellarator data). Moreover, when the stellarator discharge reaches a radiative high density limit, the radiative collapse is benign in comparison to the density limit disruption of the tokamak. These findings indicate that a stellarator reactor will optimally operate at a high density with the benefits of faster alpha-particle slowing-down (greatly reducing the drive for Alfven eigenmode and energetic-particle instabilities and reduced ripple-driven alpha losses) and detached divertor operation to reduce the peaking of the divertor loading. Without the obvious need for steady-state current drive, stellarators do not suffer from the conflicting requirements of low density for efficient auxiliary current generation and high density for tolerable divertor power loading.

These merits of the stellarator as a toroidal confinement system directly address the Greenwald Panel report's questions 4-5 (Control and Off-normal Plasma Events), and more indirectly question 6 (Plasma Modification by Auxiliary Systems). The stellarator concept resolves the gap G-6 (Ability to operate in steady-state without off-normal plasma events).

The knowledge of stellarator plasma behavior is sufficiently mature at the present time that a number of realistic reactor studies (ARIES-CS, FFHR, HSR. SPPS) have been carried out to produce credible design concepts for stellarator power plants. These studies find the projected cost of electricity to be competitive with that from tokamak power plants over a broad range of configurations and aspect ratios, demonstrating that the stellarator concept possesses a flexible path to a power plant. The ARIES-CS study is particularly useful in identifying specific aspects of the stellarator approach that require further focus in proceeding to a DEMO-scale facility. They include: validation or understanding of prompt alpha losses and localization of the strike points, global energy confinement scaling, operational limits (including plasma beta), start-up and plasma profile control, and coil complexity. These issues are among those considered in this report.

III. Identification of categories and issues

The charge to the Toroidal Alternates Panel requests the identification of the scientific and technical issues that must be addressed to reach the goals for each concept. Because the fusion goal of the stellarator program is essentially the same as for the tokamak concept and the plasma parameters of both are comparable, many of the questions raised in the 2007 Greenwald Panel report are identical to issues that must be solved in stellarators as well. These include the whole range of challenges related to the Taming of the Plasma Interface (plasma-wall interactions, plasma-facing components, design of RF in-vessel components exposed to the plasma and neutron flux) and most of those related to the Harnessing of Fusion Power (fuel cycle, power extraction, fusion materials science, and general safety). The issue of measurement capability in existing and steady-state burning plasmas is also of importance to stellarators with the exception of reduced need of diagnostics for feedback plasma control. These questions will not be considered further in this report because their evaluation is adequately covered in the previous Greenwald Panel report. It is also important to recognize that the Tier 1 issues (Plasma Facing Components and Materials) identified in that report are likely to be first addressed in the tokamak burning plasma program, in which case the results should be available for use by the entire fusion program.

The specific questions that should be addressed in the course of stellarator research over the next two decades are divided into two categories:

- **Achieving predictable, high-performance steady-state, plasmas**
- **Facilitating the construction of stellarators**

The first category is clearly similar to Theme A of the Greenwald Panel report, but poses somewhat different questions with different priorities for their resolution. A unifying theme in this category is the underlying relationship of the plasma behavior to the flux surface geometry and to the 3-D coil set that produces it, with the plasma current being a minor, but not always insignificant player.

The second category accounts for the fact that while the 3-D geometry of the stellarator can provide many design options for optimizing the plasma performance, it can also make the design and building of a stellarator a more complex process than for its two-dimensional counterparts. Therefore, increased attention must be paid to the design integration and fabrication of stellarators.

A. Achieving predictable, high-performance, steady-state plasmas

A.1 Demonstrate predictive capability for high performance stellarator plasmas based on integrated theory and modeling validated by experiment. There is a need to improve the predictive understanding of all fusion systems as the fusion program enters the burning plasma era. The expense and complexity of large experiments dictate that we develop our knowledge of fusion plasmas to the fullest extent possible in integrated plasma scenarios on our existing and future facilities. This is particularly important in ITER, which will test moderate gain DT fusion in a partially self-organized plasma environment. There is a growing effort under the SCIDAC umbrella to develop a predictive capability for integrated tokamak plasmas, and this should be extended to include stellarators. This capability will clearly be important for analyzing the observations from existing experiments and for planning experimental campaigns, and it will be critical for credible extrapolation to larger stellarator devices. The stellarator simulation effort would leverage off of the existing tokamak projects by extending codes that are being developed for tokamaks to three-dimensional geometry, and it would also include codes developed primarily in the stellarator context. Integrated modeling would be addressed, as in the tokamak context, by coupling these codes, taking advantage of the frameworks currently being developed under the auspices of the FSP program.

There are a number of areas in which integrated modeling is necessary. The stellarator coil configuration sets the flux surface geometry, and thus nominally determines transport and MHD stability through curvature, shear, and well depth. Thermal and alpha transport are influenced by symmetry and ripple placement. Divertor performance, transport barrier generation, and perhaps equilibrium β-limits are related to flux surface fragility – the possibility that non-symmetric surfaces can either become stochastic or break up into a chain of magnetic islands. The design of the coil set must simultaneously account for all such plasma physics-related issues. The particular issue of prompt alpha particle loss through residual field ripple has long been an extremely important one for stellarators. Improved, predictive models for alpha-driven instabilities and their impact on alpha particle loss locations will need to be factored in. Similarly, peaking factors of neutron and heat loading to the first wall are calculated to be higher in 3-D configurations than comparable axisymmetric devices. The 3-D coil design also imposes the need for greater engineering integration in assembling the stellarator. These integrated issues are addressed through flux surface optimization (called out as a separate issue below) such that appropriate figures of merit are simultaneously maintained if possible.

To provide validated input to integrated modeling efforts for predictive capability, there is a related need to conduct improved theory & modeling in topical areas of transport, stability, equilibrium, and heating. Key topics include (but are not confined to):

- 3D time-dependent transport code that can handle islands and stochastic regions.
- Interplay between transport driven flows, turbulence driven flows and transport barrier formation
- Understanding mechanisms of high density regimes
- Generation and consequences of energetic particle-driven instabilities in 3-D geometry
- RF heating strategies unique or well-suited to stellarators, e.g. ECH/ECCD/EBW
- Extension of fluid-based models of plasma rotation, flow, and transport to 3-D
- Extension of all theory areas (MHD/transport/gyrokinetic/heating) to incorporate

regions without closed flux surfaces

- 3-D divertor and edge modeling
- Efficient 3D equilibrium reconstruction procedures for analysis of plasma transport and stability, and for plasma control if necessary.

A.2 Determine and understand the operational limits, specifically those of plasma beta and density, in a stellarator. Understand their consequences for confinement and machine design.

The nature of the beta limit in a stellarator is not understood, and appears to be quite different than in a tokamak. While it is known from experiment that the stellarator core must have a magnetic well for stability against interchange modes, evidence from W7-AS and LHD indicates that stellarators can operate in regimes that are predicted to be unstable to Mercier and ballooning modes with little or no deterioration in plasma performance, or of disruptive activity. At the same time, equilibrium analysis of high-beta W7-AS discharges suggests that stochastization of flux surfaces may occur with increasing beta, leading to increased transport. This may effectively set a soft beta limit.

Because predictions of MHD limits impact the design of stellarator coils, there is a significant need to develop an understanding of the circumstances under which MHD instabilities correlate with deterioration of stellarator plasmas, and to develop an understanding of the conditions under which equilibrium flux surfaces are lost.

Operation of a stellarator reactor at high density would considerably ease the problems of peak divertor loading and minimize the potential for alpha-driven Alfvénic instabilites. Recent work in stellarators has been successful in obtaining reactor-relevant densities. Continuing work is needed to extend these studies to lower collisionality.

A.3 Understand and control impurity accumulation in high performance stellarator discharges

Achieving the goal of stationary steady-state plasmas in stellarators requires continued exploration and understanding of confinement modes in which impurity accumulation does not occur. Neoclassical theory predicts that for a stellarator with an electric field in the ion root, impurities will accumulate in the plasma core. This is unlike tokamaks where in the deep banana regime, a steep ion temperature gradient can lead to impurity expulsion via the temperature screening effect. It remains to be determined whether the screening effect carries over to quasi-symmetric stellarators and the degree of symmetry that is required. On the other hand, the positive electric field of the electron root at the stellarator core does lead to impurity expulsion, but the condition for the electron root ($T_e > T_i$) may not be relevant to a reactor. There is reason for optimism; in the high-density H-mode with island divertors in W7-AS, impurity confinement times are found to be low while thermal confinement remains high. The issue of impurity confinement in stellarators is a significant one. The predicted differences in neoclassical transport of impurities between tokamaks and stellarators make it useful to compare both similarities and differences between the two systems to understand the relevant mechanisms and its competition with anomalous transport.

A.4 Develop an understanding of what types of stellarator configurations are not susceptible to disruptions. More generally, determine the causes and seriousness of any "off-normal" events in stellarators

Currentless and low-current stellarators typically do not experience disruptions of the type that are of crucial importance for tokamaks. Thus disruption avoidance is not considered to be a universally important issue for stellarators. On the other hand, stellarator configurations that deliberately accommodate a significant bootstrap fraction in their optimization, e.g. QA, could conceivably suffer from current-driven disruptions under some circumstances. Knowledge is needed to determine what levels and profiles of plasma current are acceptable before disruptions appear, and if they do, how to passively avoid them. Because vacuum stellarator equilibria exist without the presence of plasma current, it is possible that disruptions in stellarators, should they occur, may have a different character than in tokamaks.

Stellarators have operated in H-mode both with and without ELMs, but ELMa are not common. The extent to which such events are tolerable in larger devices, or could be avoided should be the subject of ongoing experimental work.

A.5 Investigate the types of Internal Transport Barriers (ITBs) available to stellarator plasmas, and how they be controlled

ITBs can be generated in stellarators by various means. Higher central electron temperatures with peaked profiles have been obtained in Core Electron Root Confinement (CERC) plasmas. The ITB responsible for this regime is specific to the stellarator configuration; it is produced by bifurcation to the electron root of ambipolar transport, facilitated by finite field line ripple to enhance the collisionless electron transport. Control of the location and shear of low-order resonances of the rotational transform is also used to produce local radial electric fields for ITB generation by flow shear.

The global rotational transform and its shear can be predictably varied by changing the ratios of currents in the main equilibrium field coils. Trim coils may also be used to resonantly perturb the flux surface structure for this purpose. Plasma positioning and the use of trim coils may also be used to vary the effective ripple.

While incremental improvement in stellarator confinement is desirable, fundamental advances in this area are not absolutely required to achieve the primary goal since stellarator confinement, if it continues to follow existing scaling trends into more reactor-relevant parameter ranges, should prove acceptable for a reactor.

A.6 Determine the sensitivity of stellarator confinement and operational limits to profile variations to evaluate the need for modification of the magnetic configuration

Plasma control needs are envisioned to be a minor issue for stellarators, at least once the discharge has reached its optimum parameters. Neoclassical tearing modes are predicted to be stable in shear profile of the typical stellarator, and disruptions are not expected to be a significant problem in most configurations. Nonetheless, the sheardependent effect of low-order rational surfaces on confinement, coupled with the additional moderate rotational transform from finite bootstrap current may justify the need for some profile control, possibly during the ramp-up to high-beta in some configurations. Operating regimes with sufficiently good energetic particle confinement at reactor-relevant densities and $\langle\beta\rangle$ must be demonstrated. At issue is what level of control is needed, and how to best to apply it through auxiliary coils or other actuators.

A.7 Develop effective and workable divertors for 3-D geometry that are robust to plasma variations

Resolving the scientific and technical problems associated with high heat and particle flux to the stellarator divertor is the major step to achieving continuous, stationary discharges in a stellarator that is otherwise a natural steady-state device. (Continuously-powered heating sources and antennas are also required, of course). Divertors in 3-D pose special challenges because their helical structure must reflect the edge coil geometry, or the periodicity of the particular island chain used to create an island divertor. In the ongoing ARIES-CS reactor design study, the predicted peak divertor loading is almost a factor of two higher than the nominal engineering limit of 10 MW/m^2. As mentioned above, the high-density operating regime envisioned for stellarator reactors may reduce the problems of peaking of power deposition, and should continued to be explored as a means of resolving this issue.

A.8 Understand energetic particle-driven Alfvénic instabilities in stellarators and their impact on fast ion confinement

Alfvénic instabilities have been observed in a wide variety of stellarator configurations when an energetic particle tail is present. The three-dimensional variation of the stellarator magnetic field generates unique mode couplings and gap structures that are not present in axisymmetric devices. These features both influence the modes that can be destabilized and their damping characteristics. In addition, those stellarators that have low shear rotational transform profiles can be unstable to varieties of Alfven modes that have extended global radial mode structures. Experimental observations have indicated both regimes where such modes are relatively benign, as well as cases where such they can significantly degrade fast ion confinement and even impact thermal plasma confinement. The high density regimes obtained in LHD and W7-AS can minimize Alfvénic activity as a consequence of the shorter fast ion slowing down time, which can lower the fast ion pressure below Alfvénic stability thresholds. However, since continued access to these regimes remains to be demonstrated, improved understanding and predictability of these instabilities and their related impact on energetic particle losses and wall loading will be needed for the design and operation of future stellarators.

A.9 Continue the optimization of stellarator configurations and of 3-D plasma shaping in toroidal systems

Optimizing stellarator flux surfaces for specific physics goals coupled with the design of the coils to produce them has been one of the major transformative developments in stellarator research in the last three decades. Optimization approaches have yielded the QA, QH, QP, and quasi-isodynamic configurations, which are embodied the NCSX, HSX, QPS, and W7-X designs, respectively. It has also been conjectured that 3-D optimization could be applied to good effect on tokamaks as well. ELM suppression can be achieved with use of resonant perturbations on existing high performance tokamaks, and it is likely that additional benefits could be realized with a more systematic approach to perturbative 3-D flux surface optimization of tokamak configurations.

Configuration optimization is demonstrating benefits already. Experiments on HSX are successfully investigating the predicted effects of quasi-symmetry on neoclassical transport and viscosity. On the positive side, it is expected that further configuration optimization will continue to offer possibilities for improved plasma performance in a number of specific and integrated areas. The negative aspect of stellarator optimization is that present knowledge is not yet sufficient to unambiguously prioritize among the relatively large array of configurational parameters afforded to 3-D systems. A stellarator experiment with a given optimized coil set is somewhat limited in the range of geometries it may access and the scenarios it can test. However, the use of appropriate combinations of coil currents and auxiliary trim coils can offer a fair degree of flexibility to a single stellarator experiment. This optimization issue probably encompasses the greatest promise, and challenge, in stellarator research over the next two decades.

The correct balance in configuration optimization must be explored with improved modeling and experiment. The optimization of coils against predicted MHD limits tends to reduce the level of symmetry (at least in QA). With better understanding of actual beta limits in stellarators, optimization for desirable MHD properties could be altered in favor of other characteristics, e.g, improved collisionless transport. A major question for stellarators is what 3-D shaping (and symmetry) is optimal for confining alpha particles and reducing neoclassical and anomalous transport. The predicted prompt alpha losses in the low collisionality regime of unoptimized stellarators typically leads to unacceptable first wall damage, but optimized reactor designs show that loss rates can be manageable, particularly at high plasma density. As the relation between anomalous transport, limiting behavior, and the 3-D magnetic geometry becomes better understood, further optimization can be undertaken. Similarly, 3-D divertor design can be incorporated into configurational optimization once the relevant edge physics models are adequately validated. Electron Bernstein Wave (EBW) heating is believed to be a promising method for core heating of high-density plasmas, but requires the proper edge shear and density profiles for optimal coupling. As experimental validation and predictive understanding of stellarator plasma phenomena grow, the ability to controllably shape the 3-D configuration with external coils is envisioned to be a more universal contributor to the program's progress.

In addition to the near term program, configuration optimization will certainly be required for stellarator reactor scenarios. DEMO and burning plasmas will likely have ferritic steel near the plasma due their desirable features for the high neutron/heat flux first wall and for tritium breeding blanket modules. The impact of ferritic materials on stellarator magnetic fields and coil designs must be studied in more depth. On one hand, the presence of high-permeability steel can be expected to alter the flux surface shape from their optimal configuration. On the other hand, it is conceivable to use the saturated magnetization of ferritic steel components to produce a part of the non-axisymmetric field. Predictable deformation of the field by these elements could be useful for generating relatively high order Fourier components of the stellarator non-axisymmetric field that could not be feasibly produced by more distant coils.

The plasma aspect ratio is important in setting the projected cost of a reactor, and has emerged as a key issue in the ARIES-CS evaluation. Ongoing optimization must be continued to determine the appropriate level of compactness commensurate with wall loading (peaking), tritium breeding, divertor solutions, coil simplicity and other technical constraints.

B. Facilitating the construction of stellarators

B.1 Learn to design and construct simpler coils for stellarator configurations that retain the array of desired (e.g, quasi-symmetric) properties sufficient for practical use in reactors.

The complexity of 3-D stellarator coil systems require a significantly greater integration of physics goals and engineering practice in design, component fabrication, and assembly of stellarators than in tokamaks. To avoid magnetic islands at low order resonances, high tolerances must be achieved in winding and positioning the 3-D coils. The complex geometries and specification of tight tolerances drive costs and increase risks.

Coil sets that generate vacuum stellarator equilbria can be constructed from continuously-wound helical coils, twisted modular coils, combinations of saddle coils and planar toroidal field coils, and even combinations of planar coils. From this range of options, effort should be directed toward the design of lower cost, simplified coils that are easier to construct and assemble yet still create the stellarator configuration with the desired confinement properties. Pursuit of this issue will fold in engineering R&D of improved coil fabrication techniques with the development of a better theoretical understanding of the relationship of coil geometry to specific physics constraints. The most promising configurations must be evaluated by experiment to determine which particular coil shaping features are crucial to the design performance and which are not. This issue follows directly from, and should be considered a logical and essential continuation of the stellarator optimization process developed for the designs of HSX, NCSX, and W7-X.

Coupled with this issue is the need for better understanding of error correction techniques so that the primary coil systems can be built and positioned with lower tolerance levels. Sets of small auxiliary coils are commonly used in stellarators and tokamaks to trim out magnetic islands arising from winding errors and local magnetic materials. The same or similar coils can be used to set up ITBs, generate the proper island divertor field geometry, compensate for islands arising from finite-β, and suppress ELMs should they be an issue. More generally, a sufficiently flexible set of trim coils can be used in concert with the main field coils to controllably shape the 3-D flux surfaces, which could enable key elements of the coil optimization to be tested in a relatively few number of experiments. Effort should be directed to exploring the full range of tasks of error correction coils in stellarator geometry and how they can be most effectively implemented in practice to increase flexibility and reduce the cost and geometric complexity of the main coils themselves.

B.2 Develop advanced magnet technology for superconducting stellarator coils.

High temperature superconducting coils may relieve some of the constraints of normal superconducting magnets in a stellarator fusion device. Because they can handle higher current densities and have higher critical fields, the coils can be smaller allowing for more room for the blanket and shield, and correspondingly smaller devices operating at higher magnetic field (or lower beta). Also, the higher temperatures allow for lower cryogenic loads and less recirculating power. The steady magnetic fields of the stellarator also provide a better environment for the HTSC than in a pulsed toroidal device.

Flexible high temperature superconductor (HTSC) cable is fabricated by industry, and is presently being deployed for use in urban power transmission lines. With commercial development, dramatic decreases in cost may be expected. Stellarator research provides an excellent opportunity to initiate HTSC coil development as a transformative technology for fusion in facilitating steady-state experiments and advanced coil design.

B.3 Plan scenarios for maintaining 3D systems both with and without remote handling.

The more complex coil geometry of stellarators must be considered when optimizing for maintenance and repair. The coil design choices summarized in Issue B.1 as well as the divertor and blanket design hold implications for the methods of device assembly, disassembly, and maintenance. This issue was identified to be crucial for stellarator reactor design in recent ARIES-CS studies, and will become increasingly important as stellarator research approaches its stated goal.

Prioritization

The issues cited in the section above constitute the stellarator research areas deserving the most attention over the next two decades. Within this set, we can divide the issues into three levels of prioritization as follows:

Primary (contribution to stellarator goal essential, high promise for attractiveness of concept, comparatively limited work-to-date relative to benefits):

- Predictive capability coupled to improved topical theory and modeling
- Configuration Optimization
- Operational limits
- Simpler coil construction

Secondary (areas with considerable work performed, important for continuing progress toward goal):

- 3-D Divertor/ steady-state operation
- Disruptions, collapses, and other off-normal events
- Impurity accumulation
- Advanced coil technology

Tertiary (areas of importance and potential improvement for which sufficient capabilities are at hand, or ones that are not envisioned to limit further progress toward 20-year goal):

- Improved transport/ITB's
- Prescription of Profiles
- Maintainability/remote handling

IV. Status of issues, means to address them, and gaps

Stellarator research is being carried out worldwide to engage these issues, and others, in a variety of facilities (including the performance-class LHD and W7-X devices) and theoretical efforts. We include a representative list of stellarator facilities and key modeling codes in the Appendix; these indicate the substantial breadth and level of the research activity in the field. Also note that the capabilities and missions of the leading US and international stellarator facilities can be found in Ch. 3 of the 2007 Greenwald Panel report.

Domestic stellarator research activities include experiments, theory, and reactor studies. Until just recently, the US program was building and planning to operate the NCSX proof-of-principle (PoP) QA stellarator to perform integrated studies of confinement, MHD, stability, and power handling in a quasi-symmetric configuration. The QPS quasi-poloidally symmetric device was under design at ORNL. Both have been cancelled. Pioneering studies of electron confinement in quasi-symmetric stellarator plasmas are undertaken in HSX (QH), while issues of MHD stability and equilibrium in partially current-driven stellarators are pursued in CTH. Ultra-simple coil structures and single particle confinement are the subjects of the CNT experiment. Stellarator theory and modeling has long been a key strength of the US program, and, among other things, has produced a number of integrated tools for comprehensive configuration optimization. In identifying the key issues requiring resolution for stellarator reactors, the ARIES-CS study provides quantitative targets for the issues being addressed in current and envisioned stellarator research.

US stellarator activity is carried out in concert with a larger and more advanced international program. The operating LHD superconducting stellarator and the W7-X quasi-isodynamic optimized superconducting stellarator (under construction – projected operation in 2014)) are performance-extension class devices capable of approaching fusion-relevant conditions comparable to those attained in today's large tokamaks. Many of the important issues identified in this report will also be pursued, and on a larger scale, on foreign facilities. The US program should accordingly exhibit flexibility to engage in appropriate theoretical and experimental collaborations and comparisons with these facilities to resolve the challenges facing stellarator research today.

As a snapshot summary of the plasma parameters achieved in stellarators, we note that maximum densities of 10^{21} m^{-3}, central ion temperatures of 5.2 keV in hydrogen plasmas, $<\beta> = 4.8\%$ for over 10 confinement times in macroscopically stable plasmas, confinement enhancement factor of H = 1.5 over the ISS95 normalized stellarator scaling law, and a maximum plasma duration of 57 minutes (with 1.6 GJ total input energy) in have been obtained in separate discharges. For reference, the current projections from the ARIES-CS study for a compact stellarator reactor are $<n> = 4 \times 10^{20}$ m^{-3}, $<T_i> = 6.6$ keV, H = 2, and $<\beta> = 6.5\%$.

A.1 Predictive capability and integrated modeling

Our ability to predict stellarator behavior has benefited greatly from advances in tokamak physics. Tokamak physics is now moving into a new phase where a quantitative predictive integrated capability is being sought, and stellarator physics must also begin to move in this direction. New stellarator computational capabilities must be developed by extending tokamak codes. such as global gyrokinetic codes and extended MHD codes, to fully three-dimensional geometry. Improvements in existing stellarator codes will also be required. Integrated modeling must be addressed, as in the tokamak context, by coupling the codes, taking advantage of the frameworks being developed for tokamak codes. The codes must be validated against the large international stellarator experiments, and against the US domestic stellarator experiments.

Adequate validation of the codes against stellarator experiments will require the development and application of improved equilibrium reconstruction tools incorporating all available diagnostic data, and can handle magnetic islands and stochastic regions. The V3FIT code (under development) to perform rapid 3-D reconstructions makes use of VMEC flux surface (island-free) equilibria. A step toward reconstruction in the presence of islands has been taken by adapting the STELLOPT code to reconstruct W7-AS VMEC equilibria, and by coupling this reconstruction into the PIES code. The modeling predicts a pressure-induced stochastization of flux surfaces in the outer region of the plasma. These calculations are consistent with the reconstructed pressure profiles and with an observed degradation of confinement with increasing beta. It appears that a loss of equilibrium flux surfaces leads to a soft beta limit in at least some regimes. Further comparisons with data on the LHD, NCSX, and W7X stellarators would pin down this effect and provide an understanding of the beta constraints it imposes, and the conditions under which the effect is of importance.

There is a gap in resources for performing predictive 3-D modeling of stellarator plasmas. Under the SCIDAC umbrella, there is a growing effort to develop a predictive capability for integrated tokamak plasmas. This process should be extended to include stellarators and for modeling 3D effects in other toroidal systems as well.

A.2 Operational limits

Operational limits of pressure and density in stellarators do not lead to an abrupt termination of the plasma. Stationary values of $<\beta>$= 4.8% are achieved on LHD with transient values up to 5.0% in configurations with a central magnetic well. In W7-AS, $<\beta>$ values up to a maximum of 3.4% were achieved while linear stability calculations predicted a limit of around 2%. Operational beta limits thus far are constrained by available power rather than by stability; degraded confinement but no violent collapses have been observed.

With regard to density limits, W7-AS and LHD plasmas show evidence of a slow thermal collapse when the density exceeds a limiting value determined by the available power and impurity radiation, and can recover with a reduced particle source or higher heating power. Densities up to five times the Greenwald limit have been observed in W7-AS.

It is not believed that there is a research gap associated with this issue. Further experimental work on density and beta limits will be explored on LHD. Operational limits were to have been tested on NCSX. Results from W7-X should be available in another 10 years. In the shorter term, TJ-II is poised to obtain new results on beta limits. Theoretical understanding of MHD stability constraints is being pursued by comparisons of the predictions of linear stability codes - Terpsichore, CAS3D, COBRA and ANACONDA - against the observations of experiments. High quality equilibrium reconstructions are needed for this purpose. While good agreement has been found between the predictions of the codes and the observation of MHD activity, the observed activity has not been deleterious, and has not imposed a beta limit. Further understanding of these results will be obtained by the application of nonlinear extended MHD codes such as M3D.

A.3 Disruptions

Current-driven disruptions have been observed in earlier ohmically-heated stellarator discharges when the externally-generated transform was too low and the transform profile was unfavorable to resistive or ideal instabilities. Ohmic currents applied to W7-AS discharges (to compensate for bootstrap currents) could lead to collapses of the plasma due to tearing modes at the q=2 surface near the edge Nonetheless, disruptions were suppressed in the low-shear W7-A and JIPPT-2 stellarators if the external rotational transform comprised 15% or more of the total. Studies targeted to current-driven MHD instabilities and related 3-D equilibrium reconstruction in stellarators are underway in the small CTH device. Ideal and resistive 3-D MHD codes are available for theory and modeling related to this issue. Disruption avoidance was also to have been examined in the NCSX QA device, which would have been capable of generating substantial bootstrap current as well as having an ohmic capability in a compact configuration. While work in this area will continue, there exists a gap in evaluating ideal and resistive kink stabilities in quasi-symmetric configurations.

Bootstrap currents in LHD do not cause disruptions, and W7-X is designed to produce minimal pressure-driven currents and is not expected to experience disruptions.

A.4 Impurity Confinement

Experimentally, both TJ-II and W7-AS observe increased impurity confinement with density in some confinement regimes. ELM-free H-modes in W7-AS showed particularly strong impurity accumulation. However, with an island divertor, the even higher density HDH regime was found in which the impurity confinement dropped sharply. Calculations with the EMC3/EIRENE codes have modeled the observed transition to the high density regime in W7-AS in which impurities are expelled. Interestingly, the HDH regime exhibits a coherent fluctuation similar to that observed in diverted high-density Alcator C-Mod tokamak, in which impurity influx is also reduced. W7-X will have a similar island divertor to W7-AS, and will extend this work to higher performance plasmas. In LHD, a hollow impurity hole is observed during an ITB with high ion temperatures. In the absence of NCSX, exploration of reactor-relevant modes with low impurity confinement will continue almost exclusively on foreign stellarators.

A.5 Enhanced confinement modes/ITBs

Stellarators and tokamaks, despite relying on external coils versus internal plasma current to produce rotational transform, have similar confinement scaling. A comparison of confinement scaling amongst stellarators, however, generally shows higher confinement with reduced effective ripple. Most convincing are comparisons of different discharges on LHD that show a reduction in anomalous transport for inward-shifted configurations in which the neoclassical ripple transport is predicted to be reduced. Very recent calculations suggest that the reduction of zonal flow damping for the inward-shifted configuration may play a role in the improvement of anomalous confinement.

A variety of improved confinement regimes have been observed in stellarators including H-mode, both ELMy and ELM-free. On Heliotron-J and W7-AS, transitions to H-modes occur only in a narrow range of rotational transform. In LHD and TJ-II, transport barriers associated with magnetic islands in sheared profiles have been documented. The stellarator-specific CERC regime of improved core electron confinement observed in TJ-II, W7-AS, LHD and CHS is a neoclassical effect in which a bifurcation to an electron root in the plasma core leads to strongly peaked electron temperature profiles. High density, low impurity, good confinement regimes have been observed in both W7-AS and LHD when an island divertor was used. The Super Dense Core (SDC) regime due to an Internal Diffusion Barrier (IDB) in LHD is similar to the High Density H-mode regime (HDH) observed in W7-AS.

Further experimental work in transport will be carried out on the foreign LHD, W7-X, TJ-II, Heliotron J, H-1 stellarators, and in the US on HSX. Integrated transport studies were to be central to the mission of NCSX. A database (International Stellarator/Heliotron Profile Database) is being instituted to provide data for inter-machine comparisons. Experiments are ongoing in HSX to explore whether optimization for neoclassical transport also leads to a reduction in anomalous transport. It is also of great interest to test the possibility of accessing the supposedly ripple-dependent CERC regime in symmetric HSX plasmas. Core turbulence measurements with a reflectometer are underway on HSX, and measurement of zonal flow damping as a function of effective ripple might be possible in the edge region with probes HIBP upgrades for density and potential fluctuation measurements are under consideration.

A fundamental issue on which theoretical research is in its beginning phase is that of the interaction between neoclassical effects and turbulent transport in stellarators. Calculations are being done using the GS2 and GENE flux tube gyrokinetic codes. It will be desirable to do global gyrokinetic calculations.

A.6 Control of the configuration

Low-order resonances in the low-shear W7 and W7-AS stellarators were found to correspond to minima in global confinement, while maxima occurred at nearby irrational values of the rotational transform. Operation at rational values of the transform is typically avoided in very low shear stellarators. The bootstrap current can modify the transform profile so that low-order resonant surfaces may be shifted into or out of the confinement region, and a number of existing stellarators use modest levels of ohmic currents to modify the rotational transform profile to compensate for the bootstrap current. In future work, the low-shear W7-X will use ECCD to control internal resonances as the plasma beta is raised to its optimal value, at which point externally-driven current is no longer required. On the other hand, experiments on the moderate-shear LHD and TJ-II stellarators have shown that island chains can create internal transport barriers by generation of local radial electric fields. Such investigations will be continued on all stellarators capable of confinement studies.

Improving energetic particle confinement in the long mean free path regime by quasi-symmetry has been studied by HSX with hot electrons. NCSX would have been the only US device capable of studying hot ion confinement in a quasi-symmetric configuration in finite-beta plasmas. Experiments on W7-X will ultimately carry out those tests. The unoptimized LHD device obtains improved confinement in an inward-shifted configuration in which the effect of the instrinscally high magnetic ripple is reduced (σ-optimization). Studies of ICRH minority-heated trapped energetic protons performed in relatively low-density LHD plasmas showed the presence of confined ions up to several MeV. Further studies of RF-heated fast ions can be performed on that device in the future to determine the extent to which the heliotron concept can be extrapolated to a burning plasma configuration with good alpha particle confinement.

Sensitivity of stellarator stability and operational limits to profile variations can be studied with the Terpsichore, CAS3D, M3D, and PIES codes, although as seen from present experiments there is understanding yet to be developed. NCSX was designed with the flexibility in its main and auxiliary coil sets to investigate profile effects; integrated studies in quasi-symmetric configurations will need to await a PoP experiment Studies of profile effects can be pursued to a lesser extent on HSX and CTH.

A.7 Divertor

The outlook for progress in this area over the next twenty years is good. Useful results have already been obtained in LHD and W7-AS (the HDH mode in stellarators was discovered at the latter). Accommodating the divertor loading was crucial to obtaining the long pulse and the super-high density discharges on LHD. Sweeping of the divertor strike points was employed to distribute the thermal load in the former. W7-X will implement an island divertor in several stages, and NCSX would have been able to test relatively high heat flux to the divertor due to its compact configuration. Tests of reactor-scale heat and particle fluxes will likely be performed first in axisymmetric tokamak divertors, with results then assimilated into the stellarator divertor design.

Edge modeling calculations are using field line following for magnetic fields calculated with the MFBE/VMEC code and the PIES code to calculate the heat deposition footprint on the divertor plates, and are also using the EMC3/EIRENE code. Collaborations with the foreign experiments and the tokamak program in edge modeling need to be strengthened. Further work needs to be done to identify and incorporate desired edge features into stellarator design codes.

While W7-X and LHD will provide important experimental tests of 3-D divertor performance, they will not achieve fusion-relevant divertor fluxes. There thus remains a considerable gap in addressing divertor loading in stellarator configurations with reactor-level power and particle exhaust.

A.8 Energetic particle confinement and stability

Good initial progress has been made on the experimental diagnosis, mode identification and development of modeling tools for understanding Alfvénic modes in a variety of stellarator experiments. However, the three-dimensional magnetic field variation of the stellarator greatly increases the number of modes that can be destabilized, their degree of sideband coupling and the phase space complexity of trapped/passing particle components that can interact with such modes. New methods will need to be developed to better understand the linear drives/thresholds, nonlinear saturation mechanisms, impact on the thermal plasma, and consequences for fast ion confinement. A range of modeling approaches are under development, including improved linear analysis, extended nonlinear MHD hybrid, and full gyrokinetic methods. In addition, stellarator experimentalists have been leaders in the development of the tomographic mode structure diagnosis, escaping fast ion loss measurements and spectral analysis of these instabilities. Given the strong interest in this topic both from a fundamental physics basis and its practical importance to the design of future fusion systems, the outlook is good for further progress in understanding and predicting the impact of these instabilities. In addition, it may be possible to develop optimization targets that allow the three-dimensional shaping flexibility of stellarators to be utilized to mitigate these instabilities.

A.9 Configuration optimization

Understanding of the capabilities of stellarators has increased enormously through improved analysis and design tools. This work needs to continue to fully understand the advantages and shortcomings of the stellarator concept. Configuration optimization studies in the US have used the STELLOPT code. Improvement of optimization capabilities will follow from validation and improvement of the modules that are used to calculate the target function, and the incorporation of new modules calculating desired physics and engineering properties. It is desirable to couple virtually all codes into the optimization procedure. This was done as part the design of NCSX, using the models then available, and its experimental results would have provided a validation of those models and this integrated optimization approach. It will also be desirable to incorporate improved global search algorithms to ameliorate the problem of local minima in the high dimensional design space.

B.1 Improved coil design

The COILOPT code was used for the NCSX and QPS coil design process. It will be desirable to incorporate improved target functions representing coil complexity into the calculations, and to couple into the full configuration optimization procedure to allow for simplifications in the coil design that have minimal impact on desired configuration properties. Additional critical areas are coil accuracy and assembly tolerance. Designs need to differentiate between reproducibility and absolute accuracy in coil construction and determination of the detrimental error components (and sources) to target designs. As an example, avoiding resonances in the machine design eases requirements on error components. Compensation coils can be used to nullify the most dangerous errors. Effort should be expended in understanding these issues and in opportunities to create desired field distributions using simple coil structures.

Optimization of 3-D flux surfaces is the integrating principle of stellarator design. It requires predictive knowledge of linked areas of plasma physics, e.g. beta limits, transport, etc., coupled to the ability of designing and constructing magnet coils to efficiently produce the desired configuration, followed by testing against experiment. While elements of this process, e.g., coil design, physics understanding, are in place and can be expected to improve, there does not yet exist a strategic plan to complete this combined modeling-engineering-experimental loop in a systematic way that would lead to constructing simpler, effective coils. This is a significant gap. Combined experimental/theoretical initiatives are needed in this area, and construction of small concept-exploration facilities can be envisioned to improve the methods of constructing stellarator coil systems that are both practical and scientifically useful.

B.2 Advanced coils for stellarators

Little or no effort has been carried out to explore the potential use of HTSC in fusion experiments, although the benefits, especially to the stellarator, are enormous. This issue was identified in the Greenwald Panel report, and can be considered a gap in the stellarator research program. Opportunities exist to capture these benefits in existing fusion research institutions: a fusion magnet research group with knowledge of HTSC exists at MIT, and HTSC power cable applications are pursued at ORNL. Stellarator magnet R&D with advanced superconducting cable could both provide programmatic benefits beyond the stellarator program as well as lead to the implementation of an easier steady-state helical system. Design studies and testing of a demonstration modular coil using this commercially available product could lead to a steady-state concept exploration experiment in which the test of the suitability of HTSC in stellarators would be part of its mission.

B.3 Maintenance and remote handling of 3-D devices

A key issue for the stellarator reactor, progress in this area would follow directly from the development of less complex coil systems, and will be folded into the ARIES studies as appropriate and as concepts evolve.

V. Future plans

The international stellarator experimental program is based on three main approaches to achieving good collisionless confinement of plasmas and presenting a viable reactor candidate: the helical system approach embodied in LHD (optimized for confinement with inward shift), quasi-isodynamicity in W7-X, and quasi-symmetry. Which is the 'best' is still an open question. The performance extension experiments W7-X and LHD will provide data on two approaches. The most complete optimization, carried out on W7-X, may indeed satisfy all requirements needed to advance the stellarator concept to the DEMO level. Nevertheless, solutions to these criteria may be achieved at lower aspect ratio, or with other benefits, by employing the principles of quasi-symmetry.

NCSX was to address many of the issues described in this report in an integrated PoP-level experiment. The recent cancellation of the NCSX project will impact the ability to resolve those issues. Nevertheless, the goals of the worldwide-stellarator program remain the same in the absence of NCSX, as do the scientific and technical issues facing stellarator research. Some of the issues can be addressed by strengthening the remaining elements of the US domestic fusion program: the smaller scale domestic stellarator experiments, the international stellarator collaboration program, and stellarator theory and modeling. Furthermore, a close-out review of NCSX should be undertaken for the purpose of capturing the lessoned learned from the project construction and its cancellation. Key elements of the construction should be completed and documented in the event that the experiment could be reconstituted in some guise in the unspecified future. The strong case for quasi-symmetry still needs to be pursued to answer what is the 'best' next step for stellarator research to move toward fusion energy.

Existing experimental facilities in the US program could address some research gaps in several ways. CTH will still investigate the current limit for disruption avoidance, the effects of islands, and 3D equilibrium reconstruction, especially with improved diagnostic capability. It may be feasible to upgrade HSX with higher input power and ion heating to reach its predicted β-limit in order to understand operational limits and to achieve more reactor-relevant ion root discharges. Upgraded turbulence diagnostics could look at flow shear and zonal flows with respect to suppression of microturbulence-driven by higher curvature and shorter connection lengths with QHS.

In terms of new domestic experimental initiatives, the US could pursue the use of HTSC for stellarator magnets, as previously mentioned. A modest program would examine the compatibility of HTSC cable with modular coil designs, and if appropriate, fabricate a demonstration coil for testing. Success would open a wide design space of higher field, steady-state coils and permit stellarator devices smaller than those based on copper or conventional superconductors.

The high-value experimental niche of the US stellarator effort within the larger world program is the optimization of configurations through quasi-symmetry. The QA approach has been found worthy of investigation, and in the absence of NCSX, one can envision the possibility of designing and constructing a new Concept Exploration (CE) experiment to address the issue of quasi-axisymmetry to complement the low-current, moderate aspect-ratio QH studies in HSX. If feasible, it could use HTSC coils to operate steady-state. Optimization procedures developed for the NCSX design would be used to simplify the main field coils with the likely use of auxiliary trim coils to relax tolerances and provide flexibility. The experiment would be performed at a scale sufficient to test electron confinement in QA using ECH, and also disruption immunity with ohmic heating. It could allow for substantial divertor power and particle loading in quasi-steady-state conditions. Also, the application of removable ferritic materials for controlled 3-D field shaping for potentially improved confinement and/or stability could be tested. Pioneering experiments of the effects of optimized ferritic steel structures backed by theoretical modeling could readily be performed on CTH or CNT. Since RF power at 28 GHz is readily available within the US fusion program, we conjecture that a 1MW ECRH-heated device (at 1T) with an aspect ratio R/a = 4-5 would be sufficient for this initiative. Application of EBW for higher density operation on this device is also foreseen. Within a decade, one would want to compare the relative merits of the different approaches to symmetrization prior to initiating a PoP-scale experiment.

With domestic stellarator experiments limited in the near term to CE scale, collaboration on international experiments takes on increased importance. The need to address issues that require large machines, such as beta limits, requires that the scale of this activity be increased, with increased participation by both experimentalists and theoreticians. There are a number of key areas in which the US could provide important contributions. The subject of 3-D equilibrium reconstruction with a particular emphasis on understanding equilibrium and MHD beta limits was pursued in a collaboration on W7-AS, and extension of this activity to other international stellarators would have great value. The activity provides a valuable tool to the international stellarator community that it has lacked, while at the same time facilitating the access of US scientists to data from the large international experiments. US strengths in turbulent transport and the related area of flow shear could also be the subject of fruitful collaborations. While the US is not currently a leader in 3-D divertors, it should engage in collaborations to develop expertise in this area that will be crucial for steady-state operation. Clearly, other topics beyond these examples should also be considered.

The US has a potential opportunity to be amongst the world leaders in the development of a computational capability for predictive simulation of stellarators. Several stellarator codes that are widely used internationally have been developed in the US. Many major tokamak codes that already handle three-dimensional magnetic fields could be modified to handle stellarators with a modest effort. Under the US SCIDAC program there is a growing effort to develop an integrated predictive capability for tokamak plasmas. Extending this program to include stellarators could allow the US to become an international leader in this area, and would provide additional opportunity to validate the physics models in the tokamak codes. An improved predictive capability would feed into improved computational tools for stellarator optimization, an area where the US is already a recognized leader. Of particular interest will be the application of optimization tools to design simpler coils which preserve the desired physics properties of stellarators.

Given the continued large investment in stellarator research in the international fusion program, the US has much to gain from serious engagement in stellarator research. While the US may remain a minor partner in the near term, it could exert leading roles in a number of areas. The physics of stellarators is sufficiently close to that of tokamaks that physics insight gained in stellarator research can have an impact on the tokamak program. Perhaps more importantly, if experiments on ITER continue to maintain the desirability of pursuing stellarator concepts to resolve some of the physics and technology issues (e.g. disruptions and maintenance of steady-state operation), the US will be positioned to substantively participate in this work.

Appendix

Operating or future stellarator experiments

HSX (University of Wisconsin)
Quasi-helically symmetric CE modular stellarator; focus on configuration-optimized improved neoclassical and anomalous transport

CTH (Auburn University)
Low-aspect ratio torsatron with ohmic current; focus on disruption avoidance and equilibrium reconstruction

CNT (Columbia University)
Small stellarator with ultra-simple planar coils, focus on non-neutral transport

LHD (NIFS, Japan)
High-performance, large superconducting torsatron/heliotron with divertor; performs broad range of integrated research

Heliotron-J (Kyoto University, Japan)
Moderate-sized helical-axis heliotron, focus on effect of variable configuration controls on confinement.

TU-Heliac (Tohoku University, Japan)
Small heliac; L-H transitions in driven rotating plasmas

W7-X (IPP Greifswald, Germany)
High-performance, large, superconducting quasi-isodynamically optimized modular stellarator with divertor; under construction

WEGA(IPP Greifswald, Germany)
Older small stellarator; EBW heating

H-1 (Australian National University, Australia)
Flexible heliac; RF heating and configurational studies

TJ-II (CIEMAT, Spain)
Proof-of-principle-scale flexible heliac

L-2 (GPI, Russia)
Older, high-shear stellarator

We also note that the W7-AS modular stellarator (Germany) and CHS torsatron (Japan), though shut down in recent years, are still producing analyses of results with high impact on today's stellarator research program

Comprehensive stellarator theory and modeling tools either in use or under development

VMEC, PIES, HINT, SIESTA: 3-D equilibrium codes
CAS3D: perturbed 3-D equilibrium and stability code
STELLOPT: Multivariate optimized design of stellarators
V3FIT: 3-D reconstruction
Terpsichore: ideal stability
GS2 and GENE: flux tube gyrokinetic codes.
ORBIT: Monte Carlo code.
FULL linear microstability code (electrostatic modes).
M3D nonlinear MHD code
EMC3/EIRENE 3-D edge modeling code.
COBRA and ANACONDA ballooning stability codes.
STELLGAP and AE3D: Alfvén continuum gap structure and discrete Alfvén eigenmodes for general 3-D equilibria
PENTA: Neoclassical moments method analysis for 3-D configurations
DKES: Stellarator neoclassical transport coefficient matrix
DELTA5D: Full-f and delta-f Monte Carlo analysis for thermal and energetic particle transport in 3-D
BOOTSJ: Asymptotic, low collisionality bootstrap current