Quasi-Symmetric Stellarators as a Strategic Element in the US Fusion Energy Research Plan

Quasi-Symmetric Stellarator Research

The stellarator offers ready solutions to critical challenges for toroidal confinement fusion: it provides a steady-state, major-disruption free reactor concept with minimal recirculating power requirements for plasma sustainment. The stellarator concept has undergone a rebirth in recent years as a result of major advances in theoretical understanding, the advent of enhanced computational capabilities, and new experimental research that have substantially furthered our predictive understanding of many aspects of three dimensional magnetic confinement systems. The configurational flexibility afforded by allowing 3D shaping opens up new possible confinement regimes and optimization opportunities. This 3D magnetic design freedom allows us to test our understanding of symmetry effects on plasma confinement and to produce physics-optimized fusion configurations not possible under the constraints of axisymmetry. Historically, classical stellarators have lagged behind tokamaks in performance due to their relatively poor neoclassical confinement at low collisionality. Groundbreaking optimized designs from the 1980's, such as the W7-AS [1] in Garching, Germany and then the quasi-helically symmetric HSX [2] device in Madison, Wisconsin demonstrated that neoclassical optimization improves the thermal confinement of stellarators up to a level similar to tokamaks. The success of the initial 2016 and 2017 campaigns on the W7-X [3,4] stellarator at IPP in Greifswald, Germany, the world's first large scale neoclassically-optimized stellarator, is the most recent advance on the path to a 3D solution to the problem of maintaining fusion in steady-state. More is needed however. While the LHD stellarator in Japan and W7-X are demonstrating various advantages of the stellarator approach, *neither will explore the possible advantages of quasi-symmetry in stellarators, which is what this Strategic Element proposes.* The virtues of this Strategic Element are detailed below, and its implementation will lead to a faster, more attractive path to fusion energy realized via the stellarator concept.

Benefits of Quasi-Symmetric Stellarator Research

The fact that the stellarator generates most of its rotational transform from external coils yields significant fusion benefits. These benefits include a magnetic configuration that is inherently steady state, without the need for significant current drive or current profile control. This leads to a reactor with low recirculating power allowing an easier attainment of net electricity output [5]. Stellarators provide the ability to serve as a test bed for physics issues that arise from long pulse operation given their steady-state nature, such as plasma material interaction and impurity control. The external control of the plasma configuration, given the rigid magnetic cage provided by a field from external coils, implies that loss of equilibrium due to plasma instability and major disruption is avoided. Given the lack of major disruptions, generation of their associated runaway electrons is not of concern as in tokamaks. In addition, the stellarator has a radiative density limit set by the available heating power [6], thus allowing high density operation not constrained by Greenwald limit type phenomena [7]. This high density operation has associated benefits in terms of decreased thermalization times for energetic particles and improved energetic particle stability as well as being very desirable for divertor operation. In terms of divertor operation, long connection lengths in the 3D edge plasma can yield wider scrape-off layer (SOL) widths and heat deposition profiles. The broad range of edge magnetic configuration properties provides flexibility for edge/SOL optimization in future devices. Finally, the external control of the magnetic configuration inherent to the stellarator concept allows for more confidence in attaining the final plasma configuration based on the computational design.

Current Status of Quasi-Symmetric Stellarator Research

There are topical areas in quasi-symmetric (QS) stellarator physics for which research gaps exist [8]. The US stellarator community is well positioned to address many of these gaps. Since the design of the HSX, W7-X and NCSX configurations, there has been considerable theoretical and computational activity in these areas. These advances can be employed to embark on a new era of QS stellarator physics research with an expanded theory/computational effort, focused design activity and new experimental facilities. The main technical challenges for the existing stellarator program include:

- There has not yet been an experimental demonstration of adequate energetic ion confinement in any stellarator suitable for a reactor. Promising ideas for stellarator optimization have not been adequately explored (see e.g. [9,10,11,12]).
- A new opportunity in stellarator optimization is use of 3D shaping to affect turbulent transport (see e.g. [13,14]).
- There are unexplained low impurity regimes observed in experiments (see e.g. [15,16]).
- Divertor design is not a closed issue in the stellarator or tokamak, but potential solutions are emerging (see e.g. [17,18]). Methods for automating divertor design should be pursued.
- QS optimization allows for the presence of large flows that could benefit various confinement properties. There is a need to assess the virtues of these flows in high performance stellarators.
- It is a challenge to find reactor relevant coil designs that enable improvements in plasma confinement. However promising new coil design tools are developing (see e.g. [19,20]).

Programmatic Context

The world stellarator program is currently dominated by the large superconducting-coil facilities LHD (Japan) and W7-X (Germany). The U.S. remains active in international experimental stellarator research through a robust partnership with W7-X and targeted collaborations with LHD, both involving multiple U.S. institutions. While these programs have and will demonstrate some advantages of the stellarator approach, neither of their design approaches scale to attractive reactors. In particular, energetic ion confinement may not be adequately addressed and they only explore two of three major divertor concepts that have been identified [8]. While HSX has demonstrated the benefits of QS for electron transport, there are significant issues (ion transport, turbulence optimization, divertor design, flow physics) that need to be resolved to realize a stellarator vision for DEMO. So far, only China is pursing a QS stellarator experimental program with a budgetary commitment at the concept exploration scale. In order to fully evaluate and exploit the potential of QS stellarators for fusion, U.S. leadership and a robust, broad-based US program are required.

Proposed 15-year U.S. Research Agenda

The STELLCON report [8] outlines an approximately 20-year research plan that is summarized by the timeline in Figure 1. There are 3 basic elements of the plan:

An optimization and design initiative: A national stellarator design project should be established as soon as possible to guide the design of the two proposed new experimental facilities. A similar joint effort launched in the late 1990's produced large advances in stellarator analysis and design tools [21], deepened the understanding of QS stellarators, and produced two machine designs, for NCSX and for QPS. In the intervening years there have been advances in design tools, providing new capabilities to improve coil designs and reduce turbulent transport, resulting in better designs. At the same time, the design goals have become more challenging– new configuration designs must integrate the core, divertor, and coils in the optimization; and reactor-relevant metrics such as alpha losses and maintainability must have greater weight in the design process. In order to pool capabilities and develop designs for new experiments in the most efficient manner, the task of advancing stellarator designs is best carried out by a national team, including both university, industry, and national laboratory participants. The following elements would define the optimization strategy for this initiative:

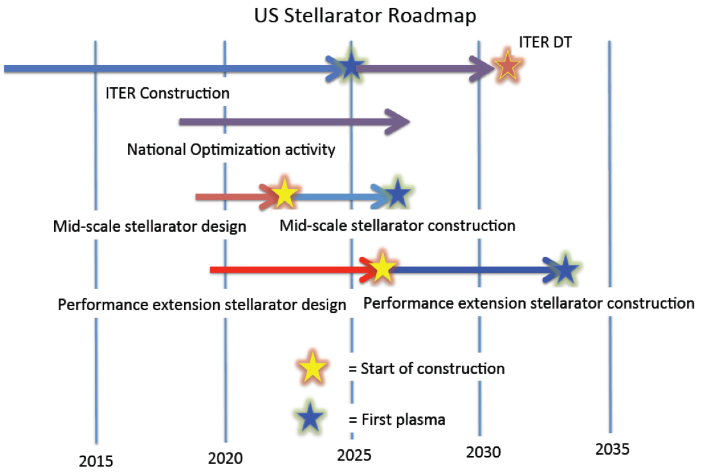

Figure 1 *Possible timeline for the major elements of the proposed reinvigorated US stellarator*

1) Optimization of neoclassical confinement through quasi-symmetry
2) Elimination of MHD instability and maintenance of good flux surfaces at finite β
3) Reduction of fast particle loss by optimization
4) Turbulent transport minimization
5) Automated divertor design consistent with optimized core
6) Coil simplification with engineering constraints to improve constructability and maintenance

A Mid-scale Facility: The design activity would lead directly to the design and construction of a new mid-scale device as soon as possible to demonstrate and test the physics basis of QS optimization by:

- Examining the physics of quasi-symmetric confinement in fusion-relevant collisionless-ion regimes with $T_i \sim T_e$
- Focusing on other issues that are not addressed in W7-X or LHD (fast particles, etc.)
- Implementing innovative design choices based on the optimization activity

Research Directions Beyond the 15-year Horizon

A Large-scale Facility: A large-scale device based on proven design principles is needed to demonstrate the required performance in fusion relevant regimes. A definitive international assessment of the potential of quasi-symmetry requires an integrated experiment, one that can answer equilibrium, stability, divertor, and energetic-particle related issues simultaneously and self-consistently. The exact requirements can only be determined by carrying out a multi-disciplinary conceptual design activity, but examples of this class of facility abound. One can anticipate that a plasma radius in the ≥ 0.5-1.0 m range, magnetic field strength in the 4 to 6 T range, and multi-10s of MW of plasma heating will be needed. Pulse length requirements are not so easily anticipated; much can be learned about divertors and plasma evolution in ~10 s pulses, but a convincing demonstration of reliable steady-state performance will likely require minutes to hours. The design may or may not include capability for DT operation, but nonetheless must be shown to be on a path to steady state nuclear facilities that are practical with respect to engineering issues such as fabrication and maintainability.

Successful implementation of this plan would place the US in a leadership position to develop an attractive stellarator-based fusion power plant in the post-ITER era.

Critics' Objections and Advocate Responses

- *Stellarators are too complicated and expensive. The 3D nature of stellarator coils make them more difficult to engineer and build.* We note that fabrication accuracies are high for all fusion systems and many devices have suffered cost overruns. The dominant source of the cost-overruns and schedule delays have been associated with high precision construction requirements, not 3D complexity [22,23]. There are several examples (W7-X, LHD) of successfully constructed large superconducting stellarator systems. Significant recent work has been done in simplifying coil designs in 3D systems [24]. Also, recent results have shown the ability to trim out error fields [25]. Stellarators coils are complex, but they provide the enormous offsetting advantages of simple operation and low recirculating power once the magnetic surfaces are created. This results in fewer and less complex auxiliary systems, greater availability, and improved operating economics. In addition, the ability to avoid major disruptions and the corresponding large transient forces, the elimination of the need for mitigation techniques simplifies the overall design. The ability to design the q-profile to avoid low order resonances is also an offsetting advantage.

- *Poor neoclassical and fast particle confinement in fusion grade plasma*. Experimental solutions with quasi-symmetry have demonstrated good confinement in smaller scale experiments and W7-X will demonstrate another optimization method (quasi-omnigeneity) to improve neoclassical confinement in a performance class device. A definitive experimental test of the efficacy of QS optimization in high performance plasmas (be it quasi-helical or quasi-axisymmetric) is needed by the world-wide fusion program. A program describing fast particle confinement optimization is described in this document.

- *Stellarators have high aspect ratio resulting in larger reactor unit sizes.* Designs exist with lower aspect ratio than present-day devices [26]. The possibility of improved confinement, due to turbulent transport optimization, could permit smaller minor radii in future devices. Moderate aspect ratio can also lower first-wall replacement demands.

- *3D divertor solutions are not yet demonstrated.* This area is a key focus of ongoing experiments and theoretical investigations. External control of the plasma edge may allow increased divertor heat flux width. Stable detachment has been demonstrated in experiments without adverse core effects [27]. High density operation also permits better divertor solutions. W7-X will demonstrate the viability of the island divertor, but the non-resonant divertor requires additional study. A reactor-relevant divertor solution is a critical area for all of magnetic fusion, and we note that such a solution has also not yet been demonstrated for tokamaks.

- *Stellarators are behind – we can't wait for them to catch up.* Because of the lower recirculating power, it may be possible to combine the FNSF and burning plasma mission with the electricity demonstration step [5]. This advantage could reduce the number of steps to a reactor.

References

---

[1] M. Hirsch, *et al., Plasma Phys. Control. Fusion* **50**, (2008) 053001
[2] J. M. Canik, *et al., Phys. Rev. Lett*. **98**, (2007) 085002
[3] H.-S. Bosch, *et al., Nucl. Fusion* **57**, (2017) 116015
[4] R.C. Wolf, *et al., Nucl. Fusion* **57**, (2017) 102020
[5] J.E. Menard, *et al., Nucl. Fusion* **51**, (2011) 103014
[6] S. Sudo, *et al., Nucl. Fusion* **30**, (1990) 11
[7] M. Greenwald, *Plasma Phys. Control. Fusion* **44**, (2002) R27-R53
[8] D. A. Gates, *et al., Journal of Fusion Energy* **37**, (2018) 51
[9] H. E. Mynick, *et al., Phys. Plasmas* **13**, (2006) 064505
[10] M. McMillan, S. A. Lazerson, *Plasma Phys. and Controlled Fusion* **56**, (2014) 095019
[11] D. Spong, S. Hirshman, J. Whitson, *Phys. Plasmas* **5**, (1998) 1752
[12] M. Drevlak, *et al., Nuclear Fusion* **54**, (2014) 073002
[13] H. Mynick *et al., Phys. Rev. Lett.* **105**, (2010) 095004
[14] C. C. Hegna, *et al., Phys. Plasmas,* **25**, (2018) 022511
[15] K. McCormack, *et al., Phys. Rev Lett.,* **89**, (2002) 015001
[16] K. Ida, *et al., Phys. Plasmas* **16**, (2009) 056111
[17] A. H. Boozer, *J. Plasma Physics* **81**, (2015) 515810606
[18] A. Bader, *et al., Phys. Plasmas* **24**, (2017) 032506
[19] M. Landreman and A. H. Boozer, *Phys. Plasmas* **23**, (2016) 032506
[20] Zhu, C., *et al., Nucl. Fusion* **58**, (2017) 016008.
[21] Spong D.A., *et al., Nucl. Fusion* **41** (2001) 711
[22] H.-S. Bosch *et al. Nucl. Fusion* **53 (**2013) 126001
[23] R. L. Strykowsky, *et al.,* in the *Proceedings of the Symposium on Fusion Energy, San Diego, CA* (2009): http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5226449
[24] D. A. Gates, *et al., Nucl. Fusion* **57**, (2017) 126064
[25] S. A. Lazerson, *et al., Nucl. Fusion* **57** (2017) 046026
[26] M. C. Zarnstorff, *et al., Plasma Phys. Control. Fusion* **43** (2001) A237
[27] Y. Feng, *et al., Nucl. Fusion* **45** (2005) 89