Control of High-Performance Steady-State Plasmas: Status of Gaps and Stellarator Solutions
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1. Introduction
The 2007 Greenwald report provided a detailed analysis of the status of magnetic fusion energy (MFE) research at that time. In response to their charge, they identified “issues arising in a path to DEMO,” and performed a gap analysis in that context, i.e. gaps in the knowledge needed for an MFE DEMO. One of Greenwald’s 15 high-level gaps, “Demonstration of integrated, steady-state, high-performance (advanced) burning plasmas, including first wall and divertor interactions” (Gap G-2), motivates stellarator research. A quantitative depiction of the gap is provided in Figure 1, adapted from [1]. Like most studies in recent years, Greenwald assumed a development path based on the tokamak, but they also reviewed stellarator issues, recognizing the stellarator as “the next most developed concept and operates intrinsically steady-state and without disruptions – two critical issues for the tokamak.”

Those advantages have earned for the stellarator a prominent place in fusion roadmap planning, especially in Europe and Japan. The U.S. has been a world leader in stellarators starting from the invention of the concept by Lyman Spitzer in the 1950s. In the 1980s, U.S. scientists advanced a new stellarator physics concept, magnetic quasi-symmetry, which provides stronger ties to the tokamak physics base and may lead to a more compact machine than previous stellarator designs. Based on this pioneering idea, small experiments were built in the 1990s at the University of Wisconsin and Auburn University, and a larger experiment, the National Compact Stellarator Experiment (NCSX) was undertaken. The NCSX was under construction at the time of the Greenwald study but was terminated due to cost over-runs shortly thereafter, although a FESAC assessment of the science of NCSX and the accompanying national program was strongly positive [2].

Since 2008, the U.S. has remained active in stellarator research through a smaller, restructured program. The Wisconsin and Auburn experiments continue to be productive, while collaborations with Japan’s Large Helical Device (LHD) project have continued, and a flourishing partnership with Germany’s new Wendelstein 7-X project has re-established a

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foothold for the U.S. to play an important role, with leadership potential, in international stellarator research. However, the loss of the former U.S. program to advance quasi-symmetry has left a significant gap in the world fusion research enterprise. In that spirit, a series of companion white papers describe a coherent set of initiatives for a renewed stellarator thrust within the U.S. Fusion Energy Sciences program.

Before turning to the gap analysis, we remark on the conventions used in the fusion community to identify the different families of concepts, “tokamaks” and “stellarators.” Tokamaks are axisymmetric (2D) and require large driven currents, while stellarators are 3D and require no current drive. In reality, the major gaps identified by Greenwald are generic to MFE. As our understanding has matured, the connections and shared properties between these two families have become better understood. The use of 3D magnetic fields, traditionally the signature characteristic of stellarators, as a way to understand and address tokamak issues has become much more widespread in the years since Greenwald. Quasi-symmetric (QS) stellarators are 3D configurations with an underlying symmetry in the magnetic field that gives them physics properties similar in important respects to those of tokamaks and other nominally axisymmetric configurations. For quasi-axisymmetric (QA) stellarators, the underlying symmetry is in the toroidal direction, and they can be viewed as a tokamak with 3D shaping. The combined knowledge of tokamaks and stellarators may be both necessary and sufficient to close those MFE gaps that are most strongly tied to the choice of magnetic configuration: sustainment, disruption avoidance, plasma confinement, and plasma-material interface.


Magnetic configuration-related issues are discussed in detail throughout the Greenwald gap analysis but the G-2 gap in integrated, steady-state, plasma performance encompasses many of them. Here we review and update the various elements of the integration challenge, emphasizing the implications for stellarators, using the same breakdown as in Greenwald Section 4.b.2:

1) Sustainment of magnetic configuration and plasma, 2) High performance burning plasma core, and 3) Edge and scrape-off plasmas.

2.1. Sustainment of magnetic configuration and plasma: control challenges vs. design.

Magnetic fusion power plants must operate in steady-state for periods of order one year without interruption. To date, most tokamak and stellarator experiments have operated for pulse lengths of 20 s or less. Pulse lengths up to an hour have been achieved, but since technical systems currently in use such as heating systems or copper magnets typically have to be de-rated for such long pulses, plasma performance in these discharges is low. Since 2007, there has been more emphasis on long-pulse operation, especially in the EAST tokamak and LHD stellarator, taking advantage of superconducting coil technology. However the gap in achieved pulse length for high-performance plasma conditions has not narrowed significantly.

A key issue for steady-state operation is control; tokamaks and stellarators represent two contrasting strategies. The tokamak relies on the injection into the plasma of energy, in the form of neutral particles or waves, to drive the required toroidal current and control the shape of its profile. But the energy efficiency of such external current drive is too low to be relied upon for driving more than 10-20% of the current. While most of the current can fortunately be self-driven by the “bootstrap” effect, it requires operation with plasma pressure and pressure gradients close to pressure limits in order to do so. Since these are determined by alpha-particle
self-heating, there is a strong non-linear coupling among confinement, sustainment, and stability, over which little control is possible. Greenwald summarized the challenges of this strategy, known as the advanced tokamak, by noting that “a fortunate coincidence is required in order for a tokamak discharge to maintain a steady state in that transport must be consistent with an optimized MHD stable pressure and bootstrap driven current profile and the concomitant alpha heating profile.”

The stellarator relies on 3D (that is, non-axisymmetric) magnetic fields designed to make a system of closed, nested vacuum magnetic surfaces without the need for current. Sustaining the magnetic configuration is therefore conceptually straightforward and stellarators such as Japan’s LHD accomplish that routinely for hours to days simply by energizing the magnets. The properties of the magnetic configuration are determined by the shape of the magnetic field, so control is largely accomplished through proper design of the magnet coil geometries. The properties can be varied to some extent during operation, if needed, by varying the ratios of currents among the different independent coil sets; assuming superconducting coils this uses no power, so a stellarator can have a high overall plant gain. The stellarator approach brings control issues of its own, as noted by Greenwald:

   Three-dimensional magnetic configurations are susceptible to deleterious effects from large magnetic islands and regions of field line ergodicity in both vacuum and finite-beta equilibria. While early stellarator experiments suffered from problems with poor-quality magnetic surfaces, by the early 1990’s both the physics understanding and the engineering capabilities needed to make geometrically accurate coil systems were well in hand. Now, stellarators can be designed and constructed to have a large volume of closed nested magnetic surfaces. By 2007, both W7-X and the U.S. NCSX project had developed designs that were predicted to be robust against magnetic surface breakup over a range of equilibrium variations with beta values extending from zero to at least 5%. These devices were both under construction at that time. Since then, an important finding from LHD shows that under the appropriate conditions, plasmas can spontaneously heal magnetic islands present in the vacuum configuration [3]. Theory suggests that this is due to plasma flow physics [4,5]. If plasma flow healing proves viable, this suggests magnetic surfaces in stellarators are more robust than the conventional 3D equilibrium tools predict. Also since 2007, the W7-X device has been built and will go into operation in 2015. The understanding of magnetic flux surface quality control will be tested, starting from the vacuum field mapping experiments that will be performed (with significant U.S. involvement) next year.

2. Energetic particle confinement.
   The ability to confine 3.5 MeV alpha particles is a basic requirement for fusion reactors. Moreover, key plasma heating methods rely on the injection or generation of superthermal ions, so energetic particle confinement is important for present-day experiments as well. Three-dimensional magnetic configurations are susceptible to large energetic particle losses, partly due to magnetic field ripple, but by 1990 design strategies to reduce such losses were available as a result of breakthroughs in physics understanding and advances in supercomputers. Machines that have been designed since then, including Wendelstein 7-X (Germany), HSX (Wisconsin), and NSCX, manifest these advances. At the time of the Greenwald report, reactor designs based on extrapolations of both the W7-X and the NCSX designs were available. Even after coil design modifications to improve the alpha
confinement in these reactor versions, significant shortfalls remained. For example, calculations for reactor designs based on the W7-X and NCSX designs predict alpha particle losses of 5-20%. Even in the best cases, 5-10% loss for ARIES-CS, the peak heat load on the divertor structures from lost alphas is too high for solid surfaces, and further improvements of configuration or materials are needed.

The potential for further improvement in this and other aspects of stellarator design is far from exhausted; both the underlying theory and the capabilities of analysis and optimization tools continue to advance, albeit currently at a slow pace. For this reason, the companion papers call for a renewed thrust in stellarator optimization, involving expanded activity in theory, simulation, and experiments, as the key theme of the U.S. stellarator strategy for the next decade.

3. MHD limits and disruptions.

Three-dimensional magnetic fields are a powerful tool for stabilizing dangerous MHD instabilities through coil design, instead of relying on fast-response operational measures to control such phenomena or mitigate their effects. An overly simple way to see it is that because the confining magnetic fields are generated by coil currents rather than plasma currents, the plasma is confined in a fixed 3D magnetic “cage” that opposes plasma geometry excursions away from equilibrium. For example, simulations of an instantaneous loss of 100% of the stored energy or current in NCSX showed that the equilibrium persists inside the material boundary with only a small radial shift. This is why stellarators provide a disruption-free solution for MFE. Early, low-beta, stellarator experiments found that disruptions were eliminated with as little as 15% of the field line “twist” (rotational transform) being provided by the externally generated 3D fields, the rest being provided by net toroidal plasma currents which were used then to Ohmically heat the plasma.

An additional benefit of 3D magnetic fields is that they provide enormous design freedom, such that designers are not limited to a single design strategy; they have flexibility in the choice and weighting of desired physics and engineering properties for targeting, and in how these properties are achieved. Stellarators can be designed for no net toroidal current or to take advantage of self-driven currents to provide a portion of the helical field-line twist. Researchers in the U.S. have used this flexibility to advantage to explore the design space for quasi-symmetric stellarators, having developed by 2007 configuration designs with low ripple (favorable for reducing collisional energy and particle transport), low flow damping (favorable for reducing turbulent transport), and stability to ideal MHD modes in high-beta (≥4%) configurations, even with significant self-driven plasma current.

By 2007 Japan’s LHD, whose design was scaled up from earlier stellarators before transport-optimization tools became widely available, had already demonstrated stable operation at beta up to 4.5%, far above predicted linear instability thresholds, in a toroidal current-free configuration. This has been extended above 5%, which was their goal. LHD research has focused on other topics since then, so this remains the world record beta for stellarators. Analysis of the LHD plasmas indicates that the confinement is degraded at high beta, possibly due to MHD instabilities and deteriorating neoclassical confinement. The W7-X design was optimized to have favorable equilibrium, stability, and confinement properties at 5% beta, in a current-free configuration. Since 2007 it has progressed through the completion of component fabrication and assembly and has begun operational commissioning preparing for first plasma in 2015. Experimental studies of high-beta, diverted 3D plasmas will be
carried out over the next several years in this $1B-class facility. The NCSX is an example of a design optimized for high-beta with 25% of the rotational transform from the bootstrap current, which the Greenwald report highlighted at the time saying, “NCSX will test the properties of quasi-axisymmetric configurations, which are predicted to have transport properties similar to tokamaks and stability properties of stellarators at moderate plasma parameters.” The absence of a plan to carry out these important experimental tests is a gap that leaves important opportunities to solve urgent MFE problems unexplored. The initiatives proposed in the companion papers include a plan to move forward with such tests.

The benefits of 3D externally-generated magnetic fields comes with a penalty in the form of geometrically complex coils, vacuum vessels, and other major structures. Achieving the tight tolerances required to achieve physics requirements for magnetic configuration accuracy, common to stellarators and tokamaks, is more difficult with stellarator geometry. Here we consider the gaps in terms of the engineering aspects affected by the geometry:

**Engineering design:** Modern tools for computer-aided design (CAD) and finite-element engineering analysis are routinely used to generate engineering models and drawings from a numerically described 3D coil design from physics. This has been well in hand for many years.

**Fabrication:** Numerically controlled tools for forming, casting, machining, metrology, etc. make it quite feasible to fabricate stellarator coils that follow a prescribed current center trajectory to millimeter accuracy. The superconducting helical-coil LHD was built in the 1990s with a custom coil winding machine and completed on schedule. Both W7-X and NCSX experienced well known schedule delays in coil manufacture. While the complex geometry and tight tolerances were contributing factors in both cases, other more generic effects such as material availability and business-related problems were at least as important. Both projects underestimated the costs of these first-of-a-kind tasks but ultimately both successfully completed the manufacture of all their non-planar coils. Feasibility is no longer an issue, but simpler geometries and improved manufacturing technology will nonetheless lead to welcome schedule and cost improvements.

**System integration, assembly, and maintenance:** The key engineering issue for stellarators resides no longer at the component level but at the system level. Large out-of-plane excursions in coil geometries, close inter-coil spacing, and tight coil-to-plasma spacing exacerbate the challenges of assembly and maintenance. There is a significant gap in the weighting that has been given to engineering objectives in stellarator optimization to date, compared to what will be needed for a practical fusion system. Since Greenwald, U.S. stellarator researchers have made progress in this area. Engineering criteria for assembly and maintenance feasibility have been identified. Coil optimization codes have undergone significant modifications in order to accommodate new criteria and to increase the design freedom available to target them without necessarily compromising physics objectives. Promising improvement strategies have been identified, but need to be implemented so that they can be tested and evaluated. The thrust in stellarator design optimization proposed in the companion papers targets engineering as well as physics aims.
2.2. High performance burning plasma core

Currently, the record triple product \((nTτ)\) for stellarators is \(5.2 \times 10^{19} \text{ keV-m}^3\text{-s}\), achieved in hydrogen plasmas in LHD. This is a factor of about 20 below that achieved in tokamaks, and about 100 below that needed for DEMO. Like tokamaks, stellarators have achieved their best triple product values in short-pulse plasmas, with durations of one second or less. For pulse lengths of several minutes to an hour, the stellarator and tokamak triple product records are comparable, about \(2 \times 10^{18} \text{ keV-m}^3\text{-s}\) in LHD and Tore Supra, respectively. Unlike tokamaks, stellarators have not operated with deuterium-tritium fuel. This gap assessment is essentially unchanged since Greenwald. The most powerful stellarator, LHD, will begin operating in deuterium in 2016. The LHD team targets a triple product value of \(\sim 1.4 \times 10^{20} \text{ keV-m}^3\text{-s}\) in deuterium which, if achieved, will be a 2.6-fold increase over values achieved in hydrogen.

Stellarators, like tokamaks, have developed an empirical confinement scaling, ISS05, from a multi-machine data base. This scaling, while based only on high-ripple stellarator data, exhibits trends that may be favorable for low-ripple optimized stellarators including QS stellarators. However, the available data from QS experiments is currently too limited to test these projections. The ISS05 scaling has been used to make reactor projections for quasi-axisymmetric stellarators, including the ARIES-CS 1 GWe power plant design \((R \approx 8 \text{ m})\) [6] and PPPL’s plant-energy breakeven pilot plant design \((R \approx 5 \text{ m})\) [7].

Stellarator optimization capabilities available in 2007 made it possible to target reduced collisional (neoclassical) transport, good energetic particle confinement, reduced flow damping, ballooning stability, negative magnetic shear, and other characteristics. While many of these are beneficial for reducing turbulent transport, which typically dominates, the capability to directly target turbulence reduction was not available. Today, several gyrokinetic codes that allow non-axisymmetric geometry are newly available, including GENE [8], FULL, GKV, and GS2 [9]. Calculation is now feasible not only of linear stability but also of saturated nonlinear turbulence over entire flux surfaces. Turbulence in both tokamaks and stellarators is strongly affected by zonal flows, and it was realized that zonal flows in stellarators have an oscillatory behavior that is not present in tokamaks [10]. Analytic understanding of microstability in stellarators has also developed; for example, it was realized that stellarators can be immune to a range of trapped-particle instabilities [11]. These advances, if validated, open new possibilities for stellarator design optimization that urgently need to be exercised and experimentally tested.

With understanding of turbulence in stellarators comes the possibility of choosing the nonaxisymmetric shaping to minimize turbulence. In a proof of concept, Mynick, et al. demonstrated it was possible to further optimize several stellarator designs, substantially reducing the turbulent transport predicted in gyrokinetic simulations [12, 13]. The authors also apply the method to a tokamak equilibrium, demonstrating in a direct way that stellarator optimization tools can benefit tokamak design and performance. This capability to reduce turbulent transport in both stellarators and tokamaks, which was not even on the horizon in 2007, opens up new possibilities for design optimization that urgently need to be exercised and experimentally tested.

For QS stellarators to have a meaningful role in the U.S. fusion roadmap, new QS experimental facilities on at least the scale and scope of NCSX will be needed. Data from such experiments would test ISS05 confinement scaling projections for low-ripple configurations and would test our understanding regarding the effects of 3D shaping on physics properties. A key question for
future QS stellarator development is whether it requires a dedicated ITER-like burning plasma step or can depend on ITER itself. Experiments in combination with appropriately focused theory and simulation research will improve understanding of the relationship between tokamaks and QS stellarators and the extent to which future QA developments can build on tokamak results, particularly burning plasma physics results from ITER.

2.3. Edge and scrape-off plasmas

As recognized by the Greenwald report, the development of plasma scenarios compatible with fusion power production and long-lived plasma-facing components (PFC) is one of the most challenging issues for magnetic confinement fusion. The core plasma must maintain sufficiently high densities, temperatures, and purity to generate fusion power, while electron temperatures at high heat-flux (~10 MW/m²) solid PFC surfaces must simultaneously be kept to <5eV to mitigate erosion by reducing physical sputtering. Extreme loads associated with “off-normal” events such as disruptions must be completely avoided.

Stellarators have advantages which may mitigate some of these issues. Stellarators can operate at high density and beta without disruptions; the increased density relative to tokamaks is expected to reduce the heat flux carried by the plasma to the targets via increased radiative losses. While ELMs (edge instabilities that in tokamaks cause repetitive intense bursts of heat to PFC surfaces) have been observed in stellarator H-modes, it may be possible to avoid them by choosing ELM-free windows in the edge transform. More generally, the flexibility in configuration space available to stellarators allows for significant freedom in the divertor design.

Pioneering island divertor experiments on W7-AS around 2000 made the very promising discovery of a new improved confinement regime called high-density H-mode (HDH) that featured strong density gradients and screening of impurities [14]. HDH-like confinement was also observed with an ergodic-field boundary in 3.5% beta experiments. The HDH mode and the scaling to a reactor will be investigated on W7-X. W7-AS did not identify a high recycling divertor regime (HRR), nor was it predicted from modeling. The lack of a HRR makes it difficult to get the volumetric power removal that may be necessary for a reactor, however HRR has been predicted to be accessible in W7-X.

Research into stellarator divertor solutions is an active area with many opportunities for world-leading research. W7-X will have the most advanced stellarator divertor system to date, an island divertor, in which toroidally and poloidally discrete divertor units are aligned relative to an edge island chain, resulting in a closed configuration similar to a tokamak x-point divertor. W7-X aims to demonstrate the feasibility of this system for stellarator reactors, with ITER-like heat fluxes (~10MW/m²) and long pulse lengths (~30 minutes). While this represents a promising solution, the non-continuous geometry is difficult to design and construct, and the plasma must be carefully controlled to maintain the island position relative to the PFCs. Active research is also occurring on the LHD stellarator, which has recently installed a helical divertor which takes advantage of the naturally diverted ergodic edge plasma. This design has been shown to be compatible with sustained high performance plasmas, however is not compatible with the discrete-coil designs of modern optimized stellarators. An open issue is divertor loads due to prompt losses of energetic alpha particles. This must be addressed in the design of a stellarator reactor, either through optimization to reduce the loss fraction, or by directing these particles to PFCs specifically designed to handle them, e.g., liquid metals.
At this time, stellarator divertor research is generally lagging in maturity compared to tokamaks in terms of designs tested, experiments with metal walls, demonstration of a high-recycling regime, etc. Since the island divertor is sensitive to variations in the edge rotational transform, control of the edge magnetic configuration is an important issue for W7-X. Neoclassical transport of impurities and the risk of their accumulation in the core requires further investigation. Enhanced divertor heat loading due to alpha losses is also a risk. The US has the opportunity to perform world-leading research in this area by taking advantage of opportunities for collaboration on the long-pulse stellarators W7-X and LHD, and by conducting well-targeted fundamental studies on domestic facilities. It is expected that the next decade will see rapid progress in stellarator divertor understanding. Improved edge and divertor models and improved methods to include divertor design criteria in the optimization process will result. Potential for a breakthrough exists in developing simplified divertor solutions compatible with quasi-symmetric configurations.

3. Community Assessments/Perspectives Since 2007

Stellarators have been addressed in all of the many FESAC and community reports that have been produced since Greenwald. These reports have consistently attached high importance to stellarator research as a route to solutions for critical MFE problems, and have recognized the potential for the U.S. to have a world-leading stellarator program. Here we briefly review this history as it pertains to stellarators.

Report of the NCSX Review Committee, FESAC, Oct. 2007 [2]: This assessment of NCSX and the accompanying national stellarator program was requested as the future of the NCSX project was being considered. The panel examined a range of program issues, including scientific issues, strengths and weaknesses of the then-called “compact stellarator” concept based on quasi-symmetry, and the role of NCSX in the international context. Their assessment was overwhelmingly positive. They were not asked to make recommendations.

Report of the FESAC Toroidal Alternates Panel, November 2008: This panel examined several magnetic configuration concepts including the stellarator, evaluating the goals, critical questions, gaps, and programs in the ITER era. They identified as the goal for stellarators, to “Develop and validate the scientific understanding necessary to assess the feasibility of a burning plasma experiment based on the quasi-symmetric (QS) stellarator.” The panel affirmed the well-known advantages of stellarators and the potential for QS configurations to deliver improved confinement and more compact designs, while noting the need for significant extrapolation in plasma parameters and for a design strategy to simultaneously address robust flux surfaces and manufacturing constraints.

ReNeW 2009 and Report of the FESAC Subcommittee on the Priorities of the Magnetic Fusion Energy Science Program (aka “Rosner Report”), April 2013: The ReNeW study provided a comprehensive and detailed portfolio of research activities needed to close the gaps identified by the Greenwald and Toroidal Alternates panels. The report identified stellarators as a “game changer” with the potential to provide innovative solutions for the high-performance steady-state burning plasma regime. A major U.S. research thrust to develop the QS concept, one of 18 described in ReNeW, was subsequently listed by the Rosner panel as one of their five highest-priority ReNeW thrusts.
FESAC Report on Opportunities for and Modes of International Collaboration in Fusion Energy Sciences Research during the ITER Era, February 2012: This panel looked at opportunities for the U.S. in long-pulse steady-state research through collaboration on overseas facilities. They identified a collaborative initiative in “Stellarator Core Performance & Edge Compatibility” as one of six such opportunities. The FES program has already moved forward on this opportunity by funding a series of in-kind contributions to W7-X of hardware (e.g., trim coils, IR camera, x-ray crystal spectrometer diagnostic, and divertor scraper) to support a U.S. research agenda that will include work on divertors, edge plasma physics, and core-edge compatibility and will contribute to narrowing the gaps in these critical areas. A recently concluded project agreement between DOE and the Max Planck Institute for Plasma Physics provides a framework for U.S. participation in all aspects of W7-X experimental research.

Report of the FESAC Subcommittee on the Prioritization of Proposed Scientific User Facilities for the Office of Science, March 2013: This panel listed a quasi-symmetric stellarator experiment as one of five new fusion facilities recommended for inclusion in the Office of Science’s plan for scientific user facilities in over the next ten years. The panel gave QS research its highest rating (“absolutely central”) for world-leading science and said, “the time is ripe to pursue a comprehensive approach to quasi-symmetric stellarators to exploit their projected benefits and deal with their presently-understood challenges in more integrated, high-performance plasma experiments.” They noted the availability of well-developed computational tools for designing optimized quasi-symmetric stellarators and existence of multiple candidates at different stages of planning and readiness for such an experiment.

Fusion Electricity: A roadmap to the realisation of fusion energy (aka “EU Roadmap”), January 2013: The European fusion community included advancement of the stellarator concept as one of eight missions on their roadmap to fusion electricity by mid-century. The plan describes the stellarator as a possible long-term alternative to the tokamak, while focusing on a tokamak path to pulsed, electricity-producing DEMO. About this strategy, the report said that it “could allow, together with the technology results from a tokamak DEMO, to build a stellarator FPP [Fusion Power Plant].”

In summary, U.S. fusion scientists have championed the innovative concept of quasi-symmetric stellarators since its inception in the pioneering work of U.S. theorists in the 1980s. Though the cancellation in 2008 of NCSX was a setback, the scientific case for such an integration step was re-affirmed by FESAC at that time and has continued to be supported nationally (and internationally) in the scientific community. Stellarator physics research in the U.S. has continued via small experiments and theory. A major collaboration with the new Wendelstein 7-X experiment, including contributions that have earned the U.S. a voice in the program planning and an opportunity to conduct world-leading research on that facility, has been put in place. Nonetheless, the gap in integrated steady-state performance for MFE that Greenwald documented in 2007 has to date not significantly narrowed. The need for stellarator solutions has only become more urgent in the intervening years. To again quote the 2013 Facilities Panel, “the time is ripe” to again move forward with this research.

4. Summary: Gap Analysis Update 2014

Although fusion has made great progress in demonstrated plasma performance, as measured by the triple product nTτ, there remains a large gap between the achieved and needed pulse lengths for high-performance plasma. The risk for fusion is such as to warrant the pursuit of multiple
solution strategies in parallel; in particular the stellarator provides a solution path to a steady-state, high performance system that is well advanced, even if it lags the tokamak in overall maturity of the concept. The U.S. fusion program for the next decade must include a strong stellarator effort as a component of its strategy to close Greenwald Gap G-2.

The status of concept-specific gaps for stellarators as of 2007 were summarized by Greenwald. In 2014, the updated status is as follows:

- The tools and knowledge to design for robust magnetic surfaces, MHD stability, neoclassical transport reduction, low plasma flow damping were available, were embodied in the NCSX non-planar coils, and were ready for integrated experimental tests at low- and high-beta. In 2014, those tests are still needed and the coils and vacuum vessel fabricated for NSCX are still available for use in a facility to carry out those tests.

- Since 2007, there have been significant advances in the understanding needed to design for turbulent transport reduction, reduced alpha particle losses, and improved engineering characteristics. In 2014, these are ready for testing in existing and new experiments and inclusion in design optimization codes.

- By 2007, the accumulated research on edge physics and divertor issues was very limited compared to core transport and stability. However, the importance was appreciated and preparations for a major expansion of this research were under way via the construction of W7-X and a major upgrade to the LHD divertor hardware. In 2014, the commissioning of W7-X has started and the LHD upgrades are completed, so the program is poised for major advances in divertor understanding in the next decade, which will factor into the design optimization of future stellarators.

- Looking beyond the coming decade to the next step, a larger facility will be needed to extend the understanding of QS stellarators to high temperature and high pressure, and extend performance to higher nTτ, longer pulses, and possible DT operation. Such a facility would test the extrapolation of confinement and performance toward burning plasmas and could produce plasmas with fusion gain Q in the range of 4-20. The program for the next ten years must include theory and simulation efforts needed to integrate physics advances into design codes that will be needed for the steps to follow.

References