Stellarator Research Opportunities

Executive summary of the STELLCON report by the National Stellarator Coordinating Committee

The STELLCON report can be found in it's entirety on the FIRE website
http://firefusionpower.org/Stellarator_Community_Report_Updated_062117.pdf

1. Executive Summary

The stellarator offers ready solutions to critical challenges for toroidal confinement fusion: it provides a steady-state, disruption-free reactor concept with minimal 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 computational capabilities, and experimental research that have made predictive understanding of many aspects of three dimensional magnetic confinement systems a reality. As a result of these advances stellarators are at the forefront of plasma physics research. The configurational flexibility afforded by the removal of the toroidal symmetry constraint opens up new physics regimes. It allows us to test our understanding of symmetry effects on plasma confinement and to produce the most physics-optimized fusion configuration yet conceived.

Historically, stellarators lagged behind tokamaks due to relatively poor neoclassical confinement. Groundbreaking optimized designs from the 1980's, first demonstrated on the W7-AS in Garching, Germany and then on the quasi-helically symmetric HSX device in Madison, Wisconsin demonstrated that neoclassical optimization improves the confinement of stellarators up to a level similar to tokamaks. The remarkable success of the initial 2016 campaign on the W7-X stellarator at IPP-Greifswald, the world's first large neoclassically-optimized stellarator, is the most recent advance on the path to a viable solution to the problem of maintaining fusion in steady-state. Progress toward steady-state (~30 min) confinement of high performance plasmas in W7-X in coming years will validate our understanding of optimized helical confinement and will establish the stellarator as a serious fusion reactor candidate.

The US has played an important role in the development of optimized stellarators. From both a theoretical [1,2] and an experimental [3,4] point of view, the US has been at the forefront of stellarator design by developing of a type of optimized configuration called quasi-symmetry. Quasi-symmetry (QS) is a hidden underlying symmetry property that leads to drift trajectories similar to those in symmetric configurations when viewed in an appropriate coordinate system. Quasi-symmetry is crucial complement to the approach taken in W7-X which is based on quasi-omnigeneity (these concepts are described within this report). Quasi-symmetry is topologically isomorphic to the tokamak, such that the large understanding accrued from the tokamak should transfer to QS stellarators. QS stellarators also allow large plasma flow velocity, which is important for achieving high confinement regimes, and introduced size flexibility. Currently, the US lacks any large-scale effort in this area. Given the exciting initial results of W7-X, and the opportunities presented by QS, a renewed US stellarator program is therefore timely.

1.1. US partnership on W7-X

OFES support for the US partnership on W7-X has made the US team (PPPL, ORNL, LANL, U. Wisconsin, Auburn U., MIT, Xantho Technologies) a key partner in W7-X, with major investments in configuration control, diagnostics, and divertor components, as well as strong participation in the research program. The primary goal of the upcoming W7-X campaign (OP1.2) will be qualification of the island divertor concept, using inertially-cooled Plasma Facing Components (PFCs). OP1.2 will be followed by an extended shutdown to install the water-cooled island divertor hardware required for OP2 operation (2019) with confinement of high performance plasmas for ~30 minutes.

W7-X is expected to show reduced neoclassical transport at high plasma pressure. Ongoing US diagnostic/modelling efforts give the US team a significant role in this research area. Key W7-X design choices led to a tight coupling of the main confinement configuration with the divertor structure. Residual pressure-driven plasma currents can change the edge rotational transform sufficiently to cause diverted heat fluxes to miss the geometrically-resonant, armored island divertor structure. Configuration control during the heating sequence is thus essential for long-pulse operation of W7-X. Investigation of these issues is the central task of the US divertor scraper project and the associated edge plasma/PMI program.

Strengthened funding for the US partnership on W7-X, building on the significant US presence there, is the quickest way to allow more US researchers (senior researchers, post-docs and graduate students) to pursue activities of strategic benefit to the US in steady-state pellet fuelling, configuration control, turbulent transport, and high-heat flux PMI.

1.2. Development of improved stellarator reactor concepts

The US stellarator theory program, which presently comprises work at PPPL, ORNL, U. Wisconsin, Auburn U., Columbia, New York University, and U. Maryland, has for some decades made major contributions to toroidal confinement physics (equilibrium, stability and transport in 3D systems), automated stellarator design optimization, and analysis of stellarator experiments. This community has also produced computational tools, which are used in stellarator research around the world.With its established expertise, the US stellarator community now has an opportunity to leverage its capabilities along with the lessons-learned from the W7-X device to develop advanced stellarator designs, which balance physics performance with robust engineering. W7-X was designed nearly 30 years ago, and there have since been numerous conceptual advances in stellarator physics and engineering that can be the basis of a world leading stellarator research program. Improved understanding from both tokamaks and stellarators enables more comprehensive optimization and identification of new approaches.

US researchers, working as a team with international collaborators, should undertake an integrated stellarator optimization initiative to test innovations that can dramatically improve plasma confinement and provide a more robust basis for the development of fusion energy. Optimized designs would combine features of neoclassically optimized high-β concepts with opportunities for new conceptual advances such as:

- Reduction of turbulent transport.
- Use of QS to improve high-energy particle confinement and reduce impurity accumulation.
- Simplified coils/support structures, with reduced non-planar distortion and increased access.
- A robust divertor system that is insensitive to the details of the equilibrium.

A successful optimization and design effort based on the above steps will lead directly to plans for enhanced research facilities.

1.3. A Forward-looking US Experimental Program

The US domestic stellarator experimental program presently comprises four university experiments. HSX (U. Wisconsin) explores the effect of quasi-symmetry on core plasma transport, flows and turbulence and in edge transport/PMI studies. The CTH stellarator (Auburn U.) studies equilibrium and stability of current-carrying stellarator plasmas. HiDRA at the U. Illinois focuses on plasma-materials interactions. The CNT device at Columbia U. is studying electron Bernstein wave heating.

To be competitive on the international scale, and greatly accelerate the pace towards stellarator fusion, a reinvigorated experimental U.S. stellarator program, based on the concept of quasi-symmetry, is needed to evaluate new optimization innovations.

In the near term, a mid-scale US facility that advances quasi-symmetry to more fusion-relevant plasma regimes and tests the non-resonant divertor concept will provide fundamental new information and guidance to the US fusion program. Such an experiment will be unique worldwide. It will also be coupled to a large experimental initiative, with the two facilities forming a complementary set.

A quasi-symmetric U.S. stellarator facility, comparable in impact with its major contemporaries like W7-X and JT60-SA, is necessary to generate information that can influence design decisions on the path toward fusion energy in the ITER era. The current lack of a clear path to steady-state, disruption-free fusion systems makes it a matter of some urgency to exploit these promising solutions as rapidly as possible. A national concept design effort for these two new facilities, the first step in translating innovative ideas into practical experimental devices, needs to start now.

References - Executive Summary

---

[1] A. H. Boozer, *Phys. Fluids* **26**, 496 (1983)
[2] H. E. Mynick, T. K. Chu, and A. H. Boozer, *Phys. Rev. Lett.* **48**, 322 (1982).
[3] F.S.B. Anderson, et al. , *Fusion Technology* **27**, 273 Suppl. S (1995)
[4] M. C. Zarnstorff, et al., *Plasma Physics and Controlled Fusion* **43** A237 (2001)

US Stellarator Roadmap