A Next Step Stellarator Experiment

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Mission

Extend the understanding of quasi-symmetric (QS) plasma confinement and integration, using 3D plasma shaping, to reactor-like conditions, producing a validated understanding sufficient to extrapolate to steady-state fusion-energy systems.

Research Summary and Contributions to world-leading science (Grade: A)

A new facility to validate the understanding of optimized 3D-shaped plasmas at burning or near-burning scale is critically needed by the US and world program, in order to provide the scientific and engineering basis for steady-state fusion energy. The proposed facility would extend the understanding of stellarators and 3D shaping to high temperature, high pressure sustained plasmas at approximately the JET-size (torus minor radius ~ 1 m), with the magnetic field sustained by external coils alone. This would be the highest performance stellarator experiment in the world and would produce world-leading science in the following areas:

- Plasma confinement properties, including operating limits, in optimized 3D configurations at high temperature, high pressure in reactor-like plasma conditions.
- Variation of 3D plasma optimized confinement processes with system size
- Integration of 3D divertor and PFC designs with high-performance core-plasma at near-burning scale.
- Validation of fusion reactivity and control using DT fuel.
- Extension and integration of simplified-coil strategies with a large scale experiment.
- Possible integration of tritium-breeding blankets with stellarator geometry.

Stellarators have long demonstrated the ability to quiescently confine plasma at high pressure without disruptions, and without the need for plasma current-drive or intensive feedback stabilization. This resolves major outstanding issues in how to go beyond ITER toward net-energy production.

The plasma shape will be optimized for good orbit confinement using quasi-symmetry and for good stability and reduced turbulent-transport based on theoretical modeling and experiments on stellarators and tokamaks. The theory of plasma transport and stability in quasi-symmetric configurations is closely related to the theory of tokamak configurations, giving confidence in modeling predictions. Aspects of this connection have been validated by HSX, which is quasi-helically symmetric (QH). Magnetic configurations with these transport and stability properties will be investigated by the proposed QUASAR experiment [1] using quasi-axisymmetry (QA), which is most-closely related to the axisymmetry of tokamaks.

Facility Description

The envisioned facility would be approximately JET scale. For a moderate aspect ratio, similar to QUASAR, this would give R in the 3 – 4.5 m range, similar to LHD, and W7-X. From a recent study of pilot-plant concepts [2], this would be expected to produce plasmas with DT-fusion gain Q in the range of 4-20, for magnetic field strengths in the range 5-6 T.

Design studies will be conducted in parallel with initial operation of W7-X and QUASAR, to prepare to start construction in ~2022, after the end of ITER construction. Operation would start ~2027, starting with DD plasmas to explore and validate confinement predictions. This would be followed by a DT phase (similar to TFTR and JET) to test plasma reactivity and control. This would provide timely results to the US and world fusion program, informing a possible path to steady-state fusion energy systems based on 3D shaping.

The facility could be designed for extensive DT operation, including breeding blankets, in order to incorporate additional mission elements. Based on initial scoping studies, a stellarator facility of this scale, can operate as a low power (100-200 MW) pilot plant, due to the low recirculating power, or as a component test facility with up to 2 MW/m^2 neutron wall loading (at 300-500 MW fusion power). Such a stellarator facility could provide a lower-risk path for these FNS (fusion nuclear science) missions, without the need to develop steady-state neutral-beams, RF launchers, or comprehensive diagnostic systems in a burning environment. Such a stellarator facility must be considered in the mission and design scoping analysis for a Fusion Nuclear Science Facility.

In parallel, additional substantial stellarator experiments (using deuterium) should be launched to explore the wide 3D shaping landscape and provide synergistic information and corroboration. Such an ensemble of experiments would inform the design of a later stellarator-based fusion power system.

Community Context

The need for a robust optimized stellarator program was identified in Renew [3] Themes 2 and 5, and specifically discussed in Thrust 17. Action 1 in Thrust 17 identifies the need for larger quasi-symmetric stellarator experiments, including a quasi-symmetric Performance-Extension (PE) experiment, such as this proposal. Such a facility would resolve all the issues in Thrust 17 and the major goal of Theme 2: creating predictable high-performance steady-state plasma confinement. It would provide alternative solutions to developing the integrated plasma control strategies, sensors, actuators, and backup strategies in Thrusts 1, 2, 5, and 8.

The design of this facility would consider and incorporate innovative new strategies to simplify stellarator coil construction and maintenance. The need for such simplifications was identified as the highest priority stellarator issue by the FESAC Toroidal Alternates Panel [4] and Renew. The design will also build upon the lessons-learned from NCSX, W7-X, LHD, and ITER construction. It will also build upon the ARIES-CS study of a competitive stellarator power system.

In the World Effort Context

The EU and Japanese fusion programs already have PE-scale stellarators as well as smaller experiments and strong theory & modeling programs. LHD (Japan) is a large (R=3.7 m) superconducting stellarator, but its design was not optimized for orbit confinement. As a consequence, it is difficult for LHD to achieve the high ion temperatures needed for fusion. LHD has shown ELMy H-mode like energy confinement and sustained plasma confinement for 54 minutes. LHD-based reactor designs have a toroidal radius of ~13 m, much larger than ITER. Wendelstein 7-X (Germany) is a large (R=5.5 m) superconducting stellarator being constructed in Germany. Its design is optimized using "quasi-omnigeneity" to minimize neoclassical transport and is predicted to have good confinement at high-pressure (β), but with minimal rotation. W-7X-based reactor designs have a toroidal radius of ~22 m and a low power density, due to their very large aspect ratio.

The proposed facility would build upon LHD and W7X results, but it would be optimized using quasi-symmetry principles to have confinement similar to or better than tokamaks, and project to a reactor size similar to tokamaks. This has already been established for quasi-axisymmetry by the ARIES-CS study. Thus, the new facility will be complementary to LHD to W7-X in the following key ways:

- Optimization by quasi-symmetry, allowing flows to reduce transport, and a close connection to tokamak physics understanding
- Compact system size, closer to tokamaks
- Use of DT fuel, to validate fusion performance and control
- Possible sustained use of DT fuel, integrating breeding blankets and Fusion Nuclear Science missions.

Construction cost estimate (Grade C: requirements and design need study)

The cost of such a facility cannot be accurately estimated before conducting a conceptual design study, and will depend on the detailed choice of mission. If the mission does not include substantial use of tritium, the cost should be approximately $1B, similar to fusion facilities of the same size such as TFTR, JET, LHD, and W7X. The cost will be significantly higher if the mission includes extensive DT operation and full breeding blankets.

Readiness

Stellarator configurations optimized for good orbit confinement have been extensively studied theoretically, and successfully explored and demonstrated in the Wendelstein 7-AS (partial QO), LHD (partial QO), and HSX (quasi-helically symmetric) experiments. LHD has achieved high pressure (1.5 atm), β=5%, and has sustained plasmas for 54 minutes. It has energy confinement similar to ELMy H-modes on tokamaks, despite not being orbit optimized. The observed energy confinement scaling is sufficient to achieve the proposed goals. Research on W7-X over the next several years should provide a full validation of the QO optimization strategy and understanding of its properties in a large plasma, including compatibility with steady-state. Hopefully, the QUASAR facility will be constructed to validate and explore QA optimization at moderate scale. Both LHD and W7-X have large program elements investigating long-pulse helical divertors, and should provide a detailed understanding of their behavior. Metalic PFCs would be used (either solid or liquid) based on tokamaks investigations and possible use on W7-X. These experiment, together with the world's tokamak experiments, would provide the basis for the detailed facility design.

The needed activities are:

- Now: Undertake a targeted R&D program to fully develop strategies for simplifying the coil engineering and device maintenance, and test them at a small scale.
- Now: Conduct pre-conceptual scoping studies and develop mission need.
- Now: Include stellarator options in the FNSF design and mission-need scoping studies [5].
- ~2017: Start conceptual design.
- ~2022: Start construction, timed to be after ITER construction funding.
- ~2027: Start commissioning and operation.

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[1] D.A. Gates et al., "QUASi-Axisymmetric Research (QUASAR) Experiment," submitted to this panel.

[2] J.E. Menard et al., Nucl. Fusion 51 (2011) 103014.

[3] Research Needs for Magnetic Fusion Energy Sciences (ReNeW) (DOE, 2009).

[4] FESAC Toroidal Alternates Report (DOE, 2008).

[5] G.H. Neilson et al., "Toward a Fusion Nuclear Science Facility," submitted to this panel.