HELIcally Optimized Stellarator: HELIOS

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Based on new experimental results from stellarators, in particular HSX, and advances in stellarator optimization design that go beyond devices presently under construction, there is a need for a magnetic confinement device in the US program whose mission is:

To explore high-density, low-current operation of an optimized quasisymmetric stellarator that has a robust divertor scalable to a reactor, no disruptions at moderate beta, good energetic ion confinement, reduced anomalous and neoclassical transport, and quiescent operation with minimal need for current profile control.

The stellarator has many advantages for fusion power applications including inherent steady-state, disruption-free operation, high density limits, no required current drive, start-up on well-formed magnetic surfaces and minimal profile control requirements. According to the FESAC ReNeW Report, "(Stellarators)…have experimentally demonstrated sustained plasmas with good confinement, high normalized pressure (β), and do not suffer from virulent current or pressure-driven instabilities that abruptly terminate the plasma." The stellarator is second only to the tokamak in parameters achieved to date. In the EFDA Report A Roadmap to the Realization of Fusion Energy, the Executive Summary states: "The stellarator is a possible long-term alternative to a tokamak Fusion Power Plant. In addition, it provides a support to the ITER physics programme."

A transformational concept in stellarator design is that of quasisymmetry (QS) which is a distinguishing feature of the US program relative to world stellarator research. It is recognized as a key element in the development of ReNeW Thrust #17. The successful design, construction and operation of the Helically Symmetric Experiment (HSX) at the University of Wisconsin-Madison and its associated physics studies detailing the advantages of quasi-helical symmetry provide an important step in fusion research. HSX, which is the first and only operating quasisymmetric stellarator, has made and continues to make fundamental contributions to the physics of quasisymmetric stellarators that show significant improvement over the conventional stellarator concept. These include:

- CXRS measurement of large (~20 km/s) flows in the direction of quasisymmetry
- Reduction of flow damping in the direction of quasisymmetry
- Reduction of passing particle deviation from a flux surface
- Reduction of direct loss orbits
- Reduction of particle and heat transport in the low collisionality regime
- Reduction of equilibrium parallel currents because of the high effective transform

Continuing a vibrant program in QS stellarator research provides an opportunity for the US program to play a leading scientific role in the worldwide program. HSX was designed specifically to demonstrate improved electron confinement and reduced flow damping. There is a need to carry this concept forward with further advancement and optimization of the stellarator concept. Because of charge exchange losses, demonstrating improved ion confinement would be better performed in a larger, high density plasma. A 3-D divertor needs to be an integral part of a design to achieve high density performance. HSX was optimized for neoclassical transport, but the possibility exists for a stellarator to be designed to reduce turbulent transport as well. In order to maintain robust equilibrium properties with finite beta, the proposed device would emphasize reduced parallel currents, a feature present in quasi-helically and quasi-poloidally symmetric configurations.

Key Elements of the Mission

While this device will build upon the successes of the domestic program, quasisymmetry, by itself, is not sufficient to advance the stellarator to the point where it could be considered a viable power plant option. Both the ReNeW and the FESAC Toroidal Alternates Panel Report identified critical areas where progress was essential to take stellarators into the "ITER era". The research gaps identified in these reports provide a primary impetus for the design principles of the proposed device. Specifically, crucial areas highlighted in the ReNeW and TAP documents include:

Divertors in 3D Configurations: While the high density operation of stellarators may ease the divertor situation somewhat (via increased radiation), it is clear that the 3D nature adds significant complexity. The island divertor concept employed for W7X should provide a workable solution for its operation, but requires control of the edge transform using current drive. This introduces control issues and scalability problems in moving toward a power plant. The helical divertor employed in LHD is not realizable with modular coil design. Robust divertor designs that require less edge plasma control and allow for expanded exhaust with rapid pumping are highly desirable. According to ReNeW: "(Divertor) designs must also be integrated with the optimization of the entire stellarator magnet system."

Energetic Ion Confinement: Optimization for good thermal confinement does not necessarily guarantee good alpha confinement, as demonstrated by the ARIES-CS study where additional contributions to the magnetic field spectrum were required to appreciably reduce alpha losses. These losses are not critical to the power balance, but rather to the wall interaction and material damage, and should be reduced by further optimization.

Coil and device simplification: Stellarator coils, modular and superconducting, have been successfully built and operated. Simplifications in coil geometries can occur with modest increases in aspect ratio from compact configurations. There is no physics drive to low aspect ratio as in a tokamak. A larger aspect ratio than the ARIES-CS reactor design would increase the tritium breeding ratio, allow for part standardization with ensuing reduced cost and ease device assembly and maintenance. Stellarator construction complexity and capital cost due to the 3-D nature can be partially offset by reduced control requirements through proper design.

Reduction of turbulent transport: Experimental work on HSX has shown that when neoclassical transport is sufficiently reduced, the dominant electron transport is anomalous. Recent gyrokinetic calculations have shown that turbulent transport can be reduced in stellarators using optimization procedures that specifically target reduced microinstability growth rates. Optimization should be targeted to reduce overall transport (neoclassical, energetic particle, and turbulent).

Configuration optimization is a sensitive function of the optimization targets and goals. There is a need to develop and experimentally investigate stellarators that address the concerns raised by the TAP and ReNeW panels for advancing into the ITER-era and beyond. At higher aspect ratio, there is more flexibility in the optimization process for overall transport optimization, space for inclusion of a robust divertor, and simplification of coil, device, and control systems.

The device would be a major component of the US program moving into the ITER-era and should operate as a user facility, supporting a broad range of scientific experimentation and education opportunities. To maximize diversity and breadth of the program it should be guided by a consortium of universities, with significant involvement of the national laboratories. Siting of the device is an open question.

Activity on the proposed facility will be complementary to existing programs. The steady-state capabilities of the stellarator are being investigated in the superconducting experiments LHD and W7X. The US already has collaborations underway with both these teams to participate in these important activities. ReNeW identified 3-D shaping as a means to improve the tokamak concept. Stellarator physicists are participating in this activity within the tokamak program. The tie between quasi and true axisymmetry at low aspect ratio and high currents was the focus of the NCSX project.

Basic Design Considerations

A true design effort has not been undertaken, but a rough idea of requirements, and therefore costs, can be derived from basic considerations. The mission requires sufficient plasma heating and confinement to access fusion relevant plasmas as well as test relevant divertor physics issues with power flux densities on the order of that expected in W7-X. High density operation is desirable to access high-density H-mode (HDH) and the associated favorable impurity physics properties as observed on W7-AS. The plasma density minor radius product should be large enough to permit a plasma core free from neutral domination.

Stellarator confinement times scale roughly as the product of the field strength and the plasma volume. B is a significant cost driver. Successful target plasmas and operations have been demonstrated in W7-AS at B=2.5T. This field value allows use of 70 GHz gyrotrons at fundamental, at 2nd harmonic at B=1.25 for β studies, and allows for possible upgrades to 140 GHz later in the program. Multiple 70 GHz systems are available within the fusion program. Neutral beams should be a significant heating source for high density operation, experimental flexibility, and for the energetic ion confinement studies. As a demonstration design point, we consider a simple scale-up of HSX at aspect ratio 8 (which allows sufficient room for divertor design) by a factor of two. This results in a facility somewhat larger than W7-AS and should provide sufficient plasma performance to meet all of the mission requirements. An HSX times two configuration is characterized by:

R=2.4m, <r> = 0.3m, B=2.5T and a volume of ~ 4 m^3

Using the conservative ISS95 confinement scaling, a heating power of 4 MW, and the Sudo density limit (power balance) gives the following estimates: heating power density = $1 W/cm^3$, τ_E=43 ms (at a line average density of 8 x 10^{13} cm^{-3}), density limit of 2.4 x 10^{14} cm^{-3}, na =2.4 x 10^{15} cm^{-2}, T_e=T_i=1keV, β=1%, and P/S=0.3 MW/m^2, (P is power through the separatrix area S).

Cost estimates are rough due to design uncertainties and site cost credits, but the following arguments support the cost as being in the appropriate range of the charge. Scaling up from HSX, a doubling of size gives a factor of 4-8, and a doubling of the field gives a factor ~4, or a scaling between 16 and 32. The cost for HSX to CD-4 (initial operation) was ~$6M, for a projected cost of $100M-$200M. Scaling down from W7-X, with an assumed $1B price, gives $90M-$180M, in reasonable agreement. With a seven year period from CD-2 to CD-4, one would expect the ongoing operating costs to be in the range $15M-$30M, using a flat construction profile converting to operating at CD-4. These levels are consistent with what one expects for a major element of the future program and with past experience, and is within the scope of the charge from the Office of Science.

Ability to contribute in the 2014-2024 timeframe

The arguments for CD-0 have largely been identified through the ReNeW process and broadly accepted by the community. The mission statement and basic design requirements set the basis for a device that would clearly contribute to advancing the stellarator concept. The mission fills an identified need in the program in concert with international activities. A plausible timeline for the implementation of the device would be:

CD-0	CD-1	CD-2	CD-3	CD-4
2013	2015	2016	2018	2023

The timeline is aggressive, but achievable, allowing operation within the desired period.

Readiness

HSX has demonstrated some of the key benefits of quasisymmetry. There is a sound basis for the use of optimization approaches in stellarator design. There are design and engineering issues presently open that need to be resolved before a conceptual design would be presented at CD-1. Tools are in place for much of the required work. Activities are already underway to answer many of these design questions, specifically with regard to divertor structure, energetic particle confinement improvement, and reduction of anomalous transport. It is expected that these issues can be conceptually resolved by 2015-2016, and fully incorporated into final design by the time of cost and schedule baselining and formal project start at CD-3 in 2018. In this respect the project is ready now to begin moving through the formal approval, design, and construction process.