A mid-scale quasihelically symmetric experiment would significantly accelerate fusion development through the stellarator line

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A mid-scale quasihelically symmetric stellarator would set the stage for a rapid progression to a D-T stellarator facility leading to a net-electric pilot plant with low recirculating power. Many fundamental advantages associated with quasisymmetry have already been demonstrated experimentally for quasihelical symmetry. New paradigms in stellarator research point to the possibility of combining, for the first time, reduced turbulent transport by design with a custom-fit divertor and plasma-material interface. A program is proposed within a manageable budget envelope which could produce potentially transformative results when undertaken within the context of the international program. This would put the US program into a strong leadership position.

The stellarator offers a viable path for the fusion energy mission.

With the confining magnetic fields all produced through use of external conductors, there is no need for a large plasma current to provide confinement; the stellarator is intrinsically a steady-state device.[1] There is no need for complex current drive systems, large bootstrap currents or profile control systems to keep those currents aligned. Lack of these systems minimizes recirculating power, reduces complexity, and improves availability in a reactor embodiment. Having only small plasma currents removes a major drive for instabilities. No major disruptions, with an associated dump of the main poloidal field magnetic energy, occur in low current stellarators. Thermal collapses can occur as in all systems, but are benign as the confining poloidal field remains in place during the event. First wall damage due to runaway electrons is not an issue in stellarators.

Density limits in stellarators are set by simple power balance. No deleterious consequences such as off-normal events occur with higher density operation. Increased density limits provide significant design space operating point options. Empirical scaling shows energy confinement time improvement with plasma density. Higher density operation may be beneficial for divertor solutions and edge radiation capabilities. Higher density operation at fixed fusion power reduces the energetic particle fraction for alpha particle driven instabilities and reduces the alpha particle slowing down time.

Transport in stellarators does not exhibit ‘stiffness’ as in tokamaks, resulting in a more diverse range of plasma profiles. In particular, there is no requirement of a pedestal in order to reach high core temperatures. The lack of significant plasma currents coupled with lower edge gradients lowers the drive for peeling-ballooning modes at the edge, so that stellarator plasmas can operate with low ELM activity. Stability to neoclassical tearing modes can be attained by proper choice of the magnetic shear; a design parameter in a stellarator.

Significant progress in understanding of divertor concepts for stellarators has been made recently and several promising features were identified. Longer connection lengths from the plasma edge to the wall offer the ability for cross-field transport to compete with parallel transport giving broader heat flux profiles on the divertor plates. At high densities, stable detached plasmas have been observed in stellarators. A stellarator would be an ideal device for materials and PMI testing when combined with the inherent steady-state nature of stellarators and high density operation.

Quasihelical symmetry offers significant benefits for the stellarator approach

Conventional stellarators have a combination of toroidal and helical curvature so that collisionless particles trapped in the magnetic ripple can drift out of the confinement region. Stellarators therefore must be optimized for good confinement. This can be accomplished through quasi-omnigeneity (QO, as in W7-X) or through quasisymmetry (QS). Quasisymmetry allows for low viscous damping, neoclassical transport equal to or better than an equivalent tokamak, and good energetic particle confinement. Quasisymmetry optimizes trapped particle confinement over a broad region of pitch angle space and permits large plasma flow in the direction of symmetry. In contrast, a QO stellarator is optimized over a narrow region of pitch angle space and heavily damps plasma flow in all directions. Within the quasisymmetric family there are two main classes. The quasiaxisymmetric stellarator (QAS) has minimal helical curvature to improve particle transport and plasma flow is optimal in the toroidal direction. The quasihelical stellarator (QHS) in contrast has minimal toroidal curvature and the plasma flow is optimal in the helical direction.

The Helically Symmetric Experiment (HSX) at the University of Wisconsin-Madison is the only quasisymmetric stellarator in the world. It is the proof-of-principle experiment that successfully demonstrated the ability to use three-dimensional (3D) shaping of the magnetic boundary to minimize collisional particle transport. Specifically, it showed that it was possible to build a toroidal device with no toroidal curvature.[2] Within the quasisymmetric family of stellarators, the QHS has some distinct advantages over other types of quasisymmetry. Many of these advantages have been confirmed on HSX, including:

- Reduced particle drift off flux surfaces[2]
- Improved neoclassical electron confinement[3]
- Reduced plasma flow damping[4]
- Large plasma flows in the direction of symmetry[5]
- Reduced bootstrap and Pfirsch-Schlüter currents[6,7]
- Good trapped particle confinement of high energy electrons[8]

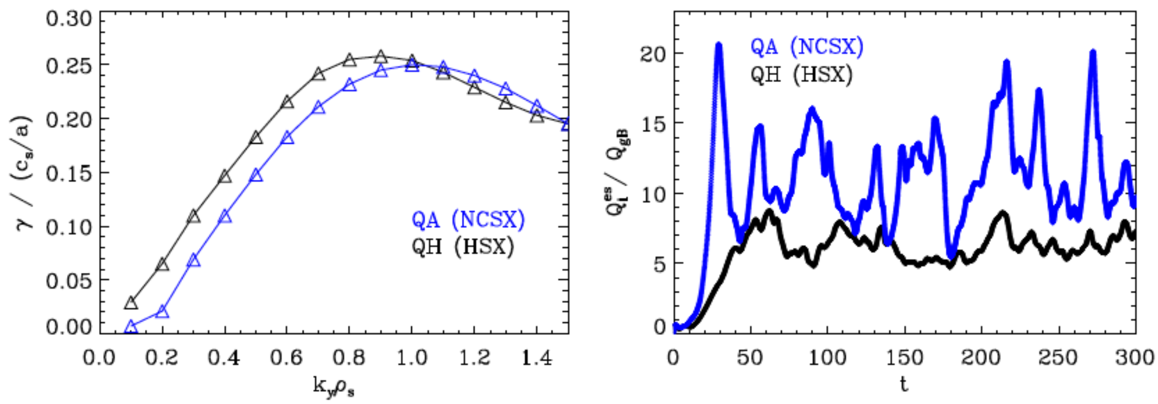
Many of the physics properties of QHS are equivalent to those of axisymmetric systems, including the tokamak, to within a coordinate transformation. Estimates for a variety of MHD and neoclassical transport physics quantities in QHS configurations can be made by replacing the safety factor scaling in familiar tokamak formulae with q_{eff} defined by[9]

$$q_{eff} = \frac{1}{N_p - \iota\!\!-}$$

where N_p is the toroidal periodicity of the magnetic field. With $N_p = 4$ and $\iota\!\!- \sim 1$, HSX effectively operates like a $q_{eff} \sim 1/3$ tokamak. As the banana widths and pressure driven currents (both Pfirsch-Schlüter and bootstrap) scale with q_{eff}, QHS has reduced values of these quantities relative to quasiaxiymmetric stellarators and tokamaks (for which $N_p = 0$ and $q_{eff} = q$). As bootstrap currents are less prominent in QHS relative to QAS, current driven instability is less of a concern in QHS configurations. Moreover, reduced Pfirsch-Schlüter currents denote smaller Shafranov shifts in QHS at the same plasma β thus making the magnetic configuration more robust to changes in plasma stored energy. This also enables reliable operation over a broad range of plasma parameters from plasma startup to high performance. As MHD equilibrium properties can dictate the upper limit to available stored energy. QHS configurations have intrinsically higher equilibrium β limits ($\beta^{\mathrm{MAX}} \sim 1/q_{eff}^2$).

In principle, collisionless particle confinement can be made arbitrarily close to that of a configuration with exact symmetry, with the difference scaling as $\sim (N_p)^{-3}$.[10] This implies QHS stellarators are superior in confining collisionless trapped particles and hence have excellent energetic ion confinement.[11] HSX has already demonstrated excellent energetic electron confinement, but energetic ion confinement needs to be demonstrated experimentally. With reduced banana widths, QHS configurations have the lowest banana regime transport of any magnetic confinement configuration including the tokamak. Like other quasisymmetric configurations, the plasma flow in the symmetry direction is weakly damped, which may enable reduced turbulent transport via sheared flow. Also, the enhanced flow provides magnetic surface healing in finite-β plasmas to avoid persistent island formation.[12,13]

QHS has some intrinsic advantages relative to other configurations with regard to turbulent transport. Emerging theoretical understanding of turbulence saturation allows us to design for reduced levels of turbulent heat flux. While QHS has higher linear microinstability growth rates than other configurations, nonlinear gyrokinetic simulations show QHS has comparable or even lower levels of turbulent heat transport at the same thermodynamic gradient drive. This is illustrated in the following figure where nonlinear GENE simulations of HSX and NCSX are performed for ion temperature gradient driven turbulent ion heat flux using adiabatic electrons. As shown in the figure on the left, QHS has higher linear instability growth rates --- particularly at long wavelength where the turbulent transport dominates. However, the figure on the right shows saturated turbulent heat transport for the two configurations, showing HSX has smaller heat flux.



These results suggest that QHS configurations have an advantage with regard to nonlinear turbulent saturation processes. This results in turbulent transport rates that are lower than predicted by simple mixing length-type ($\chi \sim \gamma/k_{\perp}^2$) levels. Recent advances in turbulence saturation theory suggest that QHS has enhanced nonlinear turbulent energy transfer to damped modes relative to QAS owing to geometric differences.[14] Enhanced nonlinear energy transfer facilitates lower turbulence saturation levels and reduced heat flux. Strengthening the dominant nonlinear energy transfer channel is an attractive approach for improving confinement. This strategy is being pursued for the first time in stellarator optimization.

The QAS configuration has the advantage that it allows for the possibility of lower aspect ratios and lower output power. However, lower aspect ratios require higher current densities which increase fabrication and assembly difficulties. The ARIES-CS design pointed to major issues that required improvement for a realistic stellarator reactor: energetic ion confinement[15], acceptable divertor performance[16], and adequate tritium breeding[17]. These issues become less severe as aspect ratio is increased.

A mid-scale QHS experiment would cost-effectively position the US program for a unique large step in the stellarator as a fusion candidate

We propose an immediate start of a national mid-scale (on the order of $100 million) quasihelically symmetric stellarator, to establish the physics basis for a D-T quasisymmetric stellarator. This QHS stellarator would build on the strengths of the US program and explore topical areas that cannot be addressed by the current stellarator portfolio. The success of this program coupled with knowledge gained from the world's long pulse large stellarators, W7-X and LHD, will enable us to transition to a national D-T stellarator.

The QHS stellarator provides a novel and exciting physics mission. Based on the experiences of HSX, we know that QHS stellarators can be built, and several of the key physics benefits of the configuration have already been demonstrated. An important mission of the device is to demonstrate that one can simultaneously improve the turbulent, neoclassical and energetic ion transport in an optimized stellarator and combine this optimized core plasma with a custom-fit divertor and PMI solution. For the first time a stellarator device will incorporate the reduction of turbulent transport in optimizing the configuration.

Another mission of the device is to demonstrate good energetic particle confinement in QHS. Adequate energetic and thermal ion confinement have not been demonstrated on any stellarator. The high effective transform of a QHS configuration allows ions to enter the low-collisionality regime at lower temperatures relative to other configurations. This lowers the heating requirements for the experiment as has already been demonstrated on HSX with regard to electron transport.[3] A mid-scale device will demonstrate that QHS configurations can achieve energetic particle confinement at levels required for a D-T stellarator.

Designing divertors capable of high performance is a key issue for quasisymmetric stellarators. The island divertor in use on W7-X has several advantages; however, this concept requires precise control of the edge rotational transform by minimizing the bootstrap current. As such this may not be suitable for QHS configurations which have finite bootstrap current. Non-resonant divertors, which are resilient against equilibrium changes were recently identified as an attractive new concept for QHS configurations.[18] Recent advancements in coil design show that locations optimal for divertor placement are not overly sensitive to coil position.[19] Therefore, with appropriate design choices, we will have sufficient room to accommodate a flexible divertor test platform. Validating divertor concepts for QS devices will be a key goal for the mid-scale device.

The parameter space necessary for the confinement and equilibrium research missions will result in significant heat and particle fluxes. In addition to a divertor solution, this device will need an appropriate first wall and divertor material choice. This challenge presents itself as an opportunity to address stellarator specific PMI issues including impurity control. Advances in additive manufacturing allow the cost-effective production of 3D shaped wall elements, which can be used as test-bed for a variety of divertor and PMI concepts. This will allow extensive qualification of various divertors in conjunction with the core plasma optimization and can also provide large flexibility in the wall materials.

Goals for this device are:

- Demonstrate good electron and ion neoclassical transport at low collisionality
- Reduction of turbulent transport through 3D shaping
- Demonstrate good energetic ion confinement
- Develop a scalable divertor solution
- PMI research with reactor relevant wall materials to reduce impurity influx
- Employ new advanced manufacturing techniques to reduce cost, time to completion, and schedule risk.

Accomplishing these physics and engineering goals requires a machine with a minimum size and field strength. A rough idea of the scope can be set by basic requirements. The device requires sufficient heating and confinement to achieve temperatures (~ keV) and densities ($\leq 10^{20}$ m^{-3}) of relevance for physics goals. Beam heating is desired to get hot ions and high density. Good confinement and beam target formation with ECH set $B \geq 2$T. Size is set by sufficient (density)* (minor radius) product ($\geq 10^{19}$ m^{-2}) for core neutral screening and energetic ion confinement. Heating power needs to be sufficient to get ions into a low collisionality regime, and also achieve conditions (not necessarily simultaneously) where stable detached divertors have been observed. As a feasibility point design, using ISS04 scaling laws, these conditions can be met with a device with R=1.8 m, $\langle a \rangle$=0.3 m, B=2T with 1.5-2 MW of heating. Key parameters are summarized in the table for two operating regimes: one at low collisionality and one at high density. An estimated cost on the order of ~$100M is supported by B^2*volume scaling both up from HSX and down from W7-X.

$\langle n \rangle$ 10^{19} m^{-3}	Na 10^{19} m^{-2}	N_{max} 10^{19} m^{-3}	ν*	τ (ms)	T (eV)	P/S MW/m^2
3	0.9	17	0.1	25	1100	0.2
10	3.0	17	1.3	49	640	0.2

By obtaining the critical knowledge from a mid-size QHS device, the US will position itself to where it can use the additional information from W7-X and LHD to undertake a stellarator D-T design. Other countries such as China, Germany and Japan are already actively engaging in design studies of quasisymmetric devices. China will soon begin construction of a concept exploration QAS device comparable to HSX. The quasisymmetric approach is a credible alternative to the tokamak concept. If we act now, the US can maintain its leadership position in quasisymmetric stellarators.

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