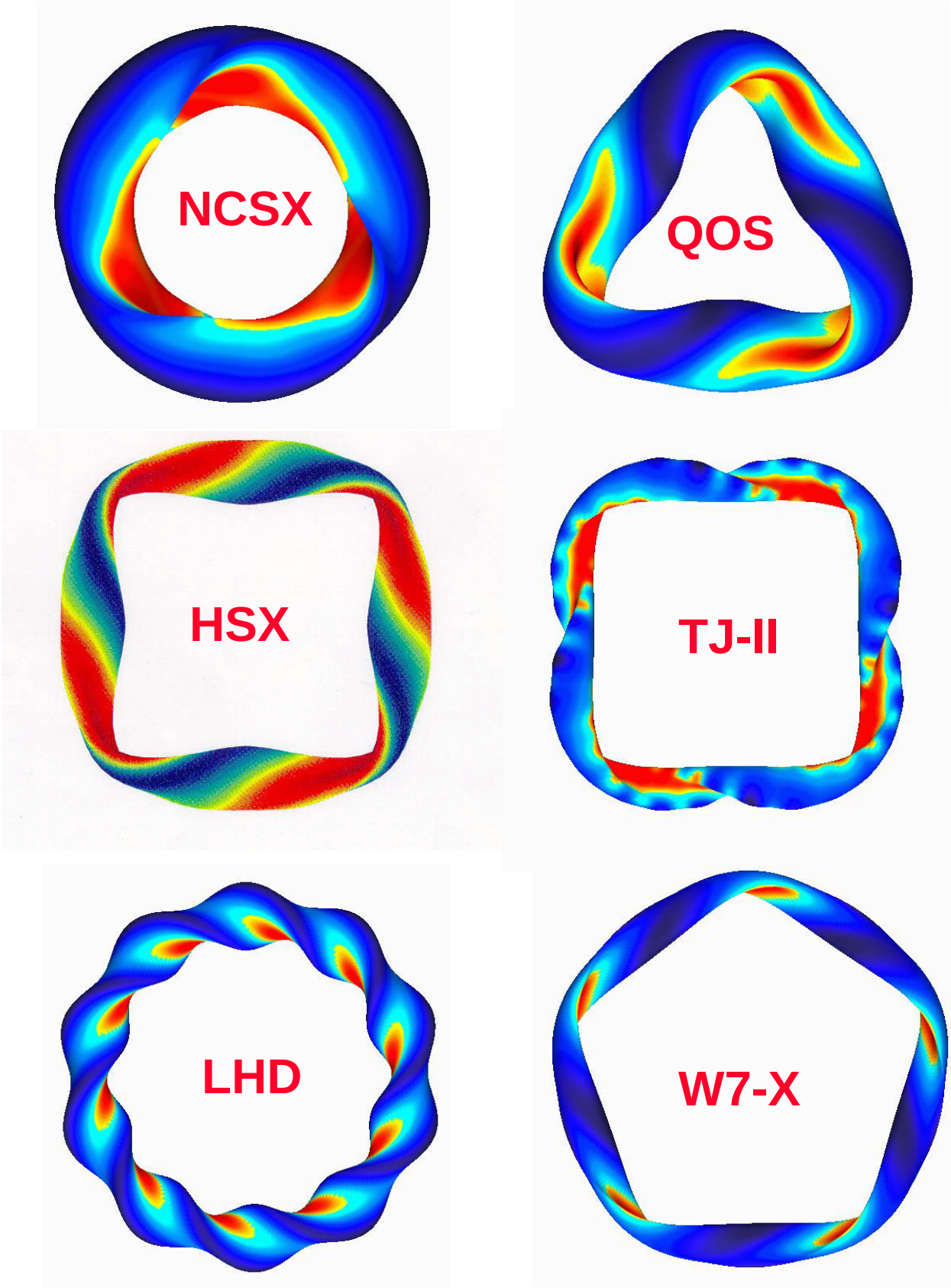
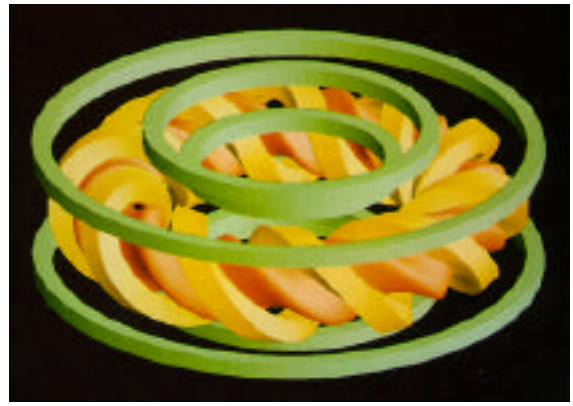
3-D Shaping of Stellarator Magnetic Surfaces (in color) Provides Flexibility to Address a Wide Range of Toroidal Physics Issues



Description

Stellarators are toroidal confinement devices with helical magnetic field lines similar to those in a tokamak, but the confining poloidal magnetic field is created by currents in non-axisymmetric coils outside the plasma, rather than by a toroidal current within the plasma. The 3-D plasma shaping in stellarators allows inherent steady-state operation with low recirculating power and avoids damaging disruptions. The flexibility of the externally generated poloidal field allows exploration of a wide range of magnetic configurations with different degrees of: helical excursions of the toroidal magnetic axis, rotation and shear in the field lines, magnetic well depth, and plasma cross section shaping and aspect ratio, the essential building blocks of toroidal confinement systems. In the large stellarator program outside the U.S., three lines of currentless stellarators with large to medium aspect ratio are being pursued. Stellarators are second only to the related tokamaks in investment, performance, and degree of physics understanding.



The LHD plasma and coil configuration.

Status: The technical basis for the design, fabrication, and projected performance of stellarators is well advanced. A confinement scaling (ISS95) based on data sets from all the world's stellarators also fits the tokamak L-mode data base.

- Experiments. The main existing experiments are the $1-billion-class Japanese superconducting-coil Large Helical Device (LHD, with R = 3.9 m, $\langle a \rangle$ = 0.65 m, $B \leq 4$ T, $P \leq 40$ MW), the Compact Helical System (CHS, with R = 1 m, $\langle a \rangle$ = 0.2 m, $B \leq 2$ T, $P \leq 2$ MW), the German Wendelstein 7-AS (W7-AS, with R = 2 m, $\langle a \rangle$ = 0.18 m, $B \leq 2.5$ T, $P \leq 3$ MW), and the smaller helical-axis stellarators (heliacs) in Australia (H-1), Spain (TJ-II), and Japan (Heliotron J).
- Theory and computational tools. Three-dimensional (3-D) codes for calculations of MHD equilibrium and stability, magnetic configuration optimization, coil optimization, and divertor topology are well-developed. 3-D neoclassical transport, including the bootstrap current, energetic orbit confinement, and ambipolar electric fields is well understood. Stellarators are now designed to meet a set of physics criteria by optimizing the shape of the plasma boundary, given the plasma pressure and current profiles, and a set of coils can then be generated to produce the desired boundary shape.
- Engineering capabilities. Computer-aided design and fabrication of complex vacuum vessels and coils is now routine as demonstrated by the successful fabrication of W7-AS, TJ-II, LHD, and the W7-X test coil. Manufacturing and assembly accuracies of <1 part in 10^3 are routinely obtained. Large superconducting coils are in use on LHD and are under construction for W7-X.

Current Research and Development

R&D Goals and Challenges

The key issues are: (1) demonstrating reduced neoclassical transport, (2) further improvement in confinement over the ISS95 scaling, (3) understanding what limits the beta in a stellarator and obtaining $\langle\beta\rangle > 5\%$, (4) obtaining parameters (T_e, T_i, $\langle\beta\rangle$, τ_E) comparable to those in the mainline tokamak, and (5) developing practical particle and power handling techniques. The non-US stellarator program is addressing these issues in large-aspect-ratio systems with very low bootstrap currents. Theoretical studies have recently identified promising concepts for "compact stellarators" that have relatively low aspect ratios and use bootstrap currents to advantage, but which are not currently being studied experimentally. A U.S. proof-of-principle program is proposed to attack the stellarator R&D issues using these new configurations as a complementary part of the world stellarator program.

Related R&D Activities

Stellarators share many physics features with tokamaks, so many of the theory and modeling tools, plasma heating systems, and results from reactor studies that are developed are useful for both. The inherently 3-D nature of stellarators allows fundamental studies relevant to a variety of 3-D plasma applications: the magnetosphere, free electron lasers, accelerator transport lattices, and non-axisymmetric perturbations to tokamaks and other toroidal confinement systems.

Recent Successes

- W7-AS: τ_E up to 2.5 times ISS95 scaling, demonstration of access to the electron root of the electric field ambipolarity condition, ICRF heating and plasma sustainment with no increase in density or impurities, and significant plasma parameters: T_e = 5.7 keV, T_i = 1.5 keV, $n_e = 3 \times 10^{20}$ m^{-3}, $\langle\beta\rangle$ = 1.8%, and τ_E = 55 ms (not simultaneously).
- LHD: τ_E up to 0.17 s, 1.5 times ISS95 scaling, and quasi steady-state operation up to 22 s with NBI in initial experiments.
- CHS: $\langle\beta\rangle$ = 2.1% and demonstrated large parallel viscous damping in a non-symmetric configuration, radial electric field control, ICRF heating of the bulk plasma, and demonstration of enhanced pumping with a local magnetic island divertor.

Budget

The world stellarator program is funded at 100-200 M$/year. DOE-OFES funded activities (≈0.8 M$ per year) on conventional stellarators principally involve collaborations on LHD, CHS, and W7-AS.

Anticipated Contributions Relative to Metrics

Metrics

- The W7-X-based Helias Stellarator Reactor (HSR, with R = 22-24 m and B = 5 T) study indicates that a stellarator reactor can be built with present superconductors (NbTi) and present physics understanding. The key measures of necessary performance are
  * neoclassical transport much less than ISS95 scaling and losses of energetic particles <~5%
  * thermal plasma confinement better than 2 x ISS95 scaling
  * plasma parameters competitive with tokamaks (T_i > 10 keV, <β> > 5%, τ_E > 0.3 s, $n\,\tau_E T > 10^{20}$ keV•s•m^{-3})
  * bootstrap current <10% of that in a comparable tokamak at high β and low collisionality
  * true steady-state operation (~1 hour) without current drive and without disruptions at <β> > 5%
  * superconducting coils with B = 5 T and fabrication and assembly accuracies <1 part in 10^3
  * practical power and particle handling schemes that are extrapolatable to a reactor-relevant configuration

Near Term ≤5 years

- LHD will extend stellarator plasma parameters to more relevant regimes (T_i ~ 10 keV, <β> ≥ 5%, τ_E > 0.2 s, $n\,\tau_E T \sim 10^{20}$ keV•s•m^{-3} with P ~ 40 MW) and study improved confinement modes, steady-state (30-minute) operation with P ~ 3 MW, simulated alpha-particle confinement, and particle control with a local island divertor.
- W7-AS will operate through 2001 and test a W7-X-relevant magnetic island divertor, operate at full power for 3-s pulses, use particle control (with the divertor and pellet injection) to test the effect on H-mode and confinement improvement and verify the density scaling of confinement, and study control of the electric field with perpendicular neutral beam injection.
- Helical-axis stellarators in Spain, Australia, and Japan will test the advantages of higher rotational transform, larger helical axis excursions, and bean cross-section shaping of the plasma with multi-MW plasma heating for a range of heliac configurations.
- Reactor studies in Germany and Japan will assess the reactor potential of the W7-X and LHD approaches.

Mid Term ~20 years

- The superconducting-coil LHD will extend operation to B = 4 T and operate with a full helical divertor in Phase II of the LHD program starting in 2001.
- The superconducting modular coil stellarator W7-X (R = 5.5 m, <a> = 0.52, B = 3 T, P = 30 MW will begin operation in 2005-6 and demonstrate low neoclassical transport, low equilibrium and bootstrap currents, a practical magnetic-island-based divertor, and more reactor-relevant plasma parameters: T > 10 keV, <β> ≥ 5%, and $n\,\tau_E T > 10^{20}$ keV•s•m^{-3}.
- If results from the world stellarator programs meet expectations, a D-T stellarator in which a large part of the power is produced by fusion reactions would be constructed at the end of this period to study the key reactor issues of thermal confinement, energetic and alpha-particle losses, MHD stability and beta limits, and steady-state particle and power handling where a significant fraction of the heating power is from fusion-generated alpha-particles.

Long Term >20 years

- Depending on results from D-T stellarator operation and the status of the world fusion program, a superconducting-coil stellarator in the DEMO class would be constructed. If successful, this would open up an inherently steady-state disruption-free route to a fusion power plant with good confinement and beta and low recycled power.

Proponents and Critics Claims

Proponents claim that: (1) stellarators can have good performance (confinement, beta) with no disruptions in true steady-state operation without the need for current drive or a potentially unstable bootstrap-current-dominated equilibrium; (2) decades of experience demonstrate that stellarators can be built with the desired accuracy; (3) the key issues for the viability of the stellarator approach wil be addressed in the large superconducting-coil stellarators LHD and W7-X; (4) the wide range of stellarator configurations extends our scientific understanding of toroidal confinement; and (5) stellarators could lead to a reactor that is more reliable than an advanced tokamak reactor and would have low recycled power. **Critics claim** that: (1) conventional stellarators lead to very large reactors; (2) helical coils are risky because they cannot be tested before the whole device is completed; (3) nonplanar coils are difficult to manufacture, are costly, and lead to too high a ratio of field on the coils to that in the plasma; and (4) stellarators have not yet demonstrated the improved confinement regimes and the particle and power handling of tokamaks.

Description

Compact stellarators, with plasma aspect ratios 1/2 to 1/3 that of conventional stellarators, are non-axisymmetric toroidal confinement devices that have helical magnetic field lines similar to those in tokamaks and conventional stellarators, but the confining poloidal magnetic field is created by both the plasma-generated internal "bootstrap" current and currents in external coils. This additional flexibility allows exploration of magnetic configurations that could combine the low aspect ratio and good performance of advanced tokamaks with the disruption immunity and low recycled power of stellarators. Two new approaches are proposed: quasi-axisymmetry (QA), which uses the bootstrap current to produce most of the poloidal field and has tokamak-like properties, and quasi-omnigeneity (QO), which approximately aligns bounce-averaged drift orbits with magnetic surfaces and aims at a smaller bootstrap current. The edge magnetic shear can be opposite to that of the advanced tokamak, stabilizing neclassical magnetic islands and permitting higher external kink stability limits without a nearby conducting wall. Complementing this is the quasi-helically symmetric (QH) approach, which produces configurations with high effective rotational transform, small deviations from a magnetic surface, and little bootstrap current. The main element of the proposed U.S. compact stellarator proof-of-principle program is the QA National Compact Stellarator Experiment (NCSX).

Status: The technical basis for design, fabrication, and projected performance of compact stellarators is well advanced. The stellarator confinement scaling ISS95 also fits the tokamak L-mode data base. Experiments on low-beta high-aspect-ratio stellarators with plasma current showed that disruptions were suppressed when the fraction of the rotational transform generated externally exceeded 20%. Control (and even reversal) of the bootstrap current and its agreement with theory has been demonstrated.

- The Helically Symmetric Experiment (HSX, with R = 1.2 m, $\langle a \rangle$ = 0.15 m, $B \leq 1.3$ T, P = 0.2 MW) at the Univ. of Wisconsin will begin operation in January 1999. It will be the world's first quasi-symmetric (QH) stellarator.
- The Compact Auburn Torsatron (CAT, with R = 0.5 m, $\langle a \rangle$ = 0.1 m) at Auburn Univ. studies field errors, plasma flow, and ICRF heating. It is being upgraded for higher magnetic field (0.5 T), higher heating power (0.2 MW), and 25-kA ohmic current.
- Theory and computational tools. The shape of the last closed flux surface determines the magnetic configuration properties and is used to both optimize those properties and to design the coils that create those configurations. 3-D codes for calculations of MHD equilibrium and stability, configuration optimization, coil optimization, and divertor geometry are well-developed. Neoclassical transport, the bootstrap current, energetic orbit confinement, and ambipolar electric fields are well understood.
- Engineering capabilities. Computer-aided design and fabrication of accurate, complex vacuum vessels and coils are now routine.
- Concept Design. The NCSX proof-of-principle facility is being designed based on a QA plasma configuration with an outer boundary shaped to satisfy physics goals: stability to ballooning and kink modes at $\langle\beta\rangle$ = 4% without a conducting wall, >50% of the poloidal field from external coils, and profiles consistent with the bootstrap current. Scoping studies for a QO concept exploration experiment with higher rotational transform are focusing on optimizing energetic particle confinement and β.

Current Research and Development

R&D Goals and Challenges

The key issues for compact stellarator configurations are: (1) demonstrating improved neoclassical transport, (2) improving confinement over the ISS95 scaling, (3) understanding what determines the limiting beta and obtaining $\langle\beta\rangle \geq 5\%$, (4) demonstrating disruption-free operation at high beta, and (5) developing practical particle and power handling approaches.

Related R&D Activities

Compact stellarators combine stellarator and advanced tokamak features in the same device and thus share many physics features with stellarators and tokamaks. Many of the physics results, theory and modeling tools, plasma heating systems, and reactor studies are useful to all three approaches. The U.S. compact stellarator program complements the large world stellarator program in which large to medium aspect ratio and low bootstrap current are emphasized. The inherently 3-D nature of compact stellarators allows fundamental studies relevant to a variety of 3-D plasma applications.

Recent Successes

- Configuration optimization codes now generate plasma configurations with specified physics properties such as drift surface alignment with magnetic surfaces, magnetic symmetry, plasma current profile, total current, rotational transform profile, magnetic well, plasma aspect ratio, magnetic field ripple, outer surface curvature, ballooning and kink stability limits, etc.
- Coil optimization codes now include desired engineering properties such as coil type (non-planar, saddle, or helical), distance between the last closed flux surface and the coil winding surface, degree of harmonic content in the coils, etc.
- QA and QO configurations have been found that should be free of disruptions with good neoclassical confinement, attractive beta limits, and practical modular coils that can take advantage of existing toroidal facilities to minimize cost.

Budget

DOE-OFES FY98: $5.9M; FY99: $8.3M. The total proposed proof-of-principle program budget (covering HSX, CAT, theory, international collaboration, and the proposed NCSX and QOS experiments) for FY00 is $15.7M, increasing to $30M/year in later years. The largest part ($20M/year) of this is for the national NCSX program, which includes an estimated $35M total project cost for NCSX construction and the budgets for research preparations, operation, and continuing facility improvements.

Anticipated Contributions Relative to Metrics

Metrics

- The 1994 Stellarator Power Plant Study indicated that a modular stellarator with R = 14 m and B = 5 T would be competitive with the second-stability ARIES-IV tokamak reactor for the same costing and materials assumptions if $\langle\beta\rangle$ = 5% and $\tau_E \geq 2$ times τ_E(ISS95). Compact stellarators offer the possibility of reducing R by a factor ~2 and higher (more economical) wall loading. Measures of the required performance are
  - * neoclassical transport much less than ISS95 scaling and losses of energetic particles <~10%
  - * thermal plasma confinement better than 2 x ISS95 scaling
  - * plasma parameters competitive with tokamaks (T_i > 10 keV, $\langle\beta\rangle$ > 5%, τ_E > 0.3 s, $n\,\tau_E T > 10^{20}$ keV•s•m^{-3})
  - * compatibility of the bootstrap current (and its control) with operation at high β and low collisionality
  - * immunity to disruptions with a large bootstrap current contribution to the rotational transform in true steady-state operation
  - * superconducting coils with B = 5 T and fabrication and assembly accuracies <1 part in 10^3
  - * practical steady-state power and particle handling schemes that are extrapolatable to a reactor-relevant configuration
  - * reactor designs with good plasma-coil spacing Δ (R/Δ < 4) and coil utilization (B_{max}/B_0) < 3

Near Term ≤5 years

- A coordinated U.S. proof-of-principle (PoP) program is proposed to attack key issues in combination with the world program.
- Two complementary compact stellarators will be built and start operation in 2003-2005: NCSX, a QA PoP experiment, and QOS, a concept-exploration-level experiment -- the new elements in the US Compact Stellarator Proof-of-Principle program.
- HSX will explore the QH approach with coils that allow the degree of symmetry, neoclassical transport, magnetic well depth, stability, rotational transform and parallel viscosity to be varied. HSX will: (1) demonstrate the reduction in particle drifts from flux surface due to large effective rotational transform; (2) test reduction of neoclassical electron thermal conductivity and direct orbit losses; (3) demonstrate whether reduction of parallel viscosity in symmetry direction decreases the momentum damping rate; and (4) explore whether large E x B shear can be obtained due to quasi-symmetry or the ambipolarity constraint.
- CAT-upgrade will investigate the disruptivity of current-carrying helical plasmas over a wide range of rotational transform profiles and test different ICRF heating scenarios for application to other stellarators.
- Scoping and ARIES studies will assess the reactor potential of compact stellarators and help define the critical issues.
- LHD will study improved confinement modes, steady-state operation, and particle control with a local island divertor.
- W7-AS will test a compact stellarator relevant island divertor, study H-mode and confinement improvement, study operation with a net plasma current and control of the electric field with perpendicular neutral beam injection.

Mid Term ~20 years

- The NCSX PoP facility (R = 1.5 m, $\langle a\rangle$ = 0.45 m, B = 1-2 T, P = 6-12 MW) will explore the QA optimization approach and address key compact stellarator issues: (1) operation at high β with bootstrap currents and external transform without disruptions; (2) understanding of β limits and the limiting mechanisms; (3) reduction of neoclassical transport to a low level by proper configuration design; (4) control of turbulent transport (e.g., by flow shear), leading to enhanced global confinment; and (5) suppression of neoclassical islands and tearing modes by bootstrap current and stellarator magnetic shear.
- The QOS concept-exploration device ($R \leq 1$ m, $\langle a\rangle$ < 0.28 m, B = 1-2 T, $P \leq 4$ MW) would test reduction of: (1) neoclassical transport via nonsymmetric QO, and the effect of electric fields on confinement; (2) energetic orbit losses in non-symmetric low-aspect-ratio stellarators; (3) the bootstrap current, its control, and the configuration dependence on β; and (4) anomalous transport by methods such as sheared E × B flow, and understand flow damping in non-symmetric configurations.
- W7-X will extend our understanding of reduction of neoclassical and anomalous transport, reduction of equilibrium and bootstrap currents, scaling of beta limits, and optimization of island-based divertors for steady-state particle and power handling.

Long Term >20 years

- If results from the total US stellarator proof-of-principle, LHD, and W7-X programs meet our expectations, a proof-of-performance superconducting-coil compact stellarator in the LHD/W7-X class would study key issues of confinement, MHD stability, and steady-state particle and power handling at T > 10 keV, $\langle\beta\rangle$ > 5%, $n\,\tau_E T > 10^{20}$ keV•s•m^{-3} with P > 30 MW and B > 3 T.
- If results from the compact stellarator proof-of-performance program and the world stellarator program are compelling, a D-T compact stellarator facility would test the feasibility of this approach to a more attractive reactor.

Proponents and Critics Claims

Proponents claim that compact stellarators could combine the low aspect ratio and good performance of tokamaks (confinement, beta) with the disruption immunity and low recycled power of stellarators. Compact stellarator configurations, stellarator-tokamak hybrids, that use the bootstrap current and quasi-symmetry or quasi-omnigeneity, would extend our scientific understanding of toroidal confinement and could lead to a reactor that is economically competitive with, but more reliable than, the advanced tokamak. **Critics claim** that nonplanar stellarator coils are difficult to manufacture, are costly, and lead to a higher ratio of field on the coils to that in the plasma, so the beta limit needs to be higher to be more attractive than in tokamaks; and that stellarators have not yet demonstrated the improved confinement regimes and the particle and power handling of tokamaks.