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 about half of the confining poloidal field and has tokamak-like symmetry 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 neoclassical 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 (PoP) 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 to $B = 0.5$ T, $P = 0.2$ MW, and 25-kA ohmic current in order to study kink stability.
- 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 PoP program budget (covering HSX, CAT, theory, international collaboration, and the proposed NCSX and QOS experiments) for FY00 would be \$15.7M, increasing to \$30M/year in later years. The largest part (\$20M/year) of this is for the national NCSX program. The proposed Compact Stellarator PoP program was reviewed favorably by a DOE review panel for PoP programs and FESAC recommended funding to maintain the program momentum.

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 PoP, LHD, and W7-X programs meet expectations, a proof-of-performance superconducting-coil and/or D-T Compact Stellarator could be used to study key issues of confinement, MHD stability, particle and power handling, and possibly D-T physics 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 the results from the above experiments prove favorable, then the next step would be a Compact Stellarator Experimental Test 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.