SCIENTIFIC ISSUES FOR THE COMPACT STELLARATOR PROGRAM

Presented by Allen Boozer
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Applied research is driven by goals and schedules. Reduction in the physics risks of DEMO provides a drive for the compact stellarator program.

I. Benefits of Non-Axisymmetric Shaping

II. Important Constraints on Non-axisymmetric Shaping

III. Research on Utility of Non-Axisymmetric Shaping

IV. Elements of the Research Program

V. Scientific Issues Summary

I. Benefits of Non-Axisymmetric Shaping

Toroidal equilibria are defined by plasma shape, q profile, and pressure profile.

Profiles are largely self-determined by a high-gain fusion plasma.

Leaves shaping as the primary means of control.

1. Robust plasma stability

   Eliminates disruptions, resistive wall modes, and neoclassical tearing modes

2. Control and maintenance of the *q* profile.

   Eliminates need for current drive and large bootstrap currents.

3. Broad range of operating densities, above the Greenwald limit.

   Higher density reduces pressure of α's, which reduces drive for Alfvén instabilities, lowers energy per particle hitting divertor plates, which reduces erosion.

All are critical issues for the path between ITER and DEMO.

Robust plasma stability with non-axisymmetric shaping

Importance

Robust stability allows operating points near limits.

Catastrophic termination of the plasma equilibrium—a disruption—is more difficult to handle the larger the machine (<1/yr in DEMO).

Forces, power deposition, runaway-electron avalanches, etc.

A large bootstrap current requires β_p / ℓ_i large, drives:

kink instabilities (resistive wall modes requiring feedback)
enhances external field-error effects.

With non-axisymmetric shaping:

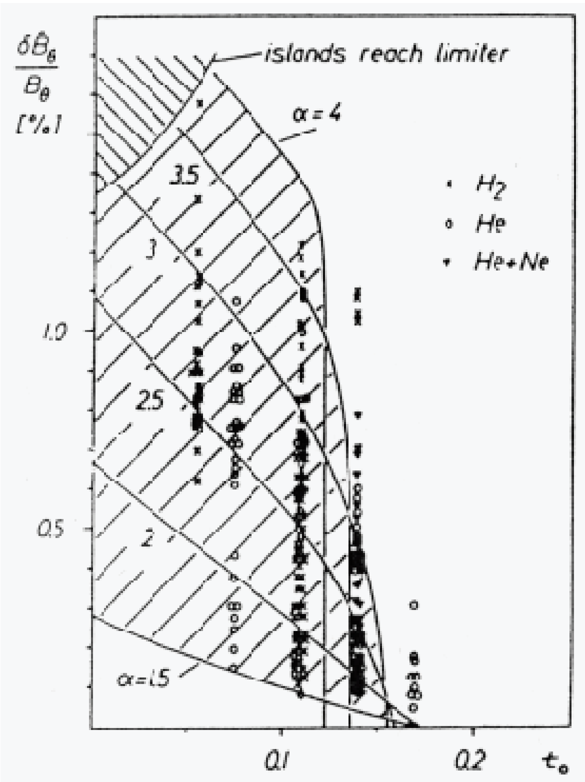
A large bootstrap current is not needed.

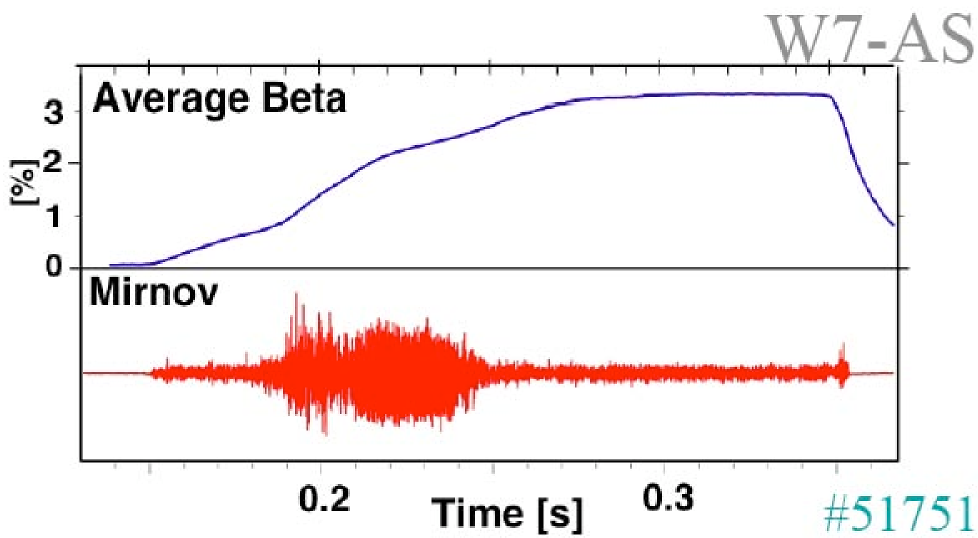
Operational limits are soft—degradation in confinement not a catastrophic termination—allowing operation nearer those limits.

Robust plasma stability

Evidence (disruptions & soft beta limit)

W VII-A, NF 20, 1093 (1980)

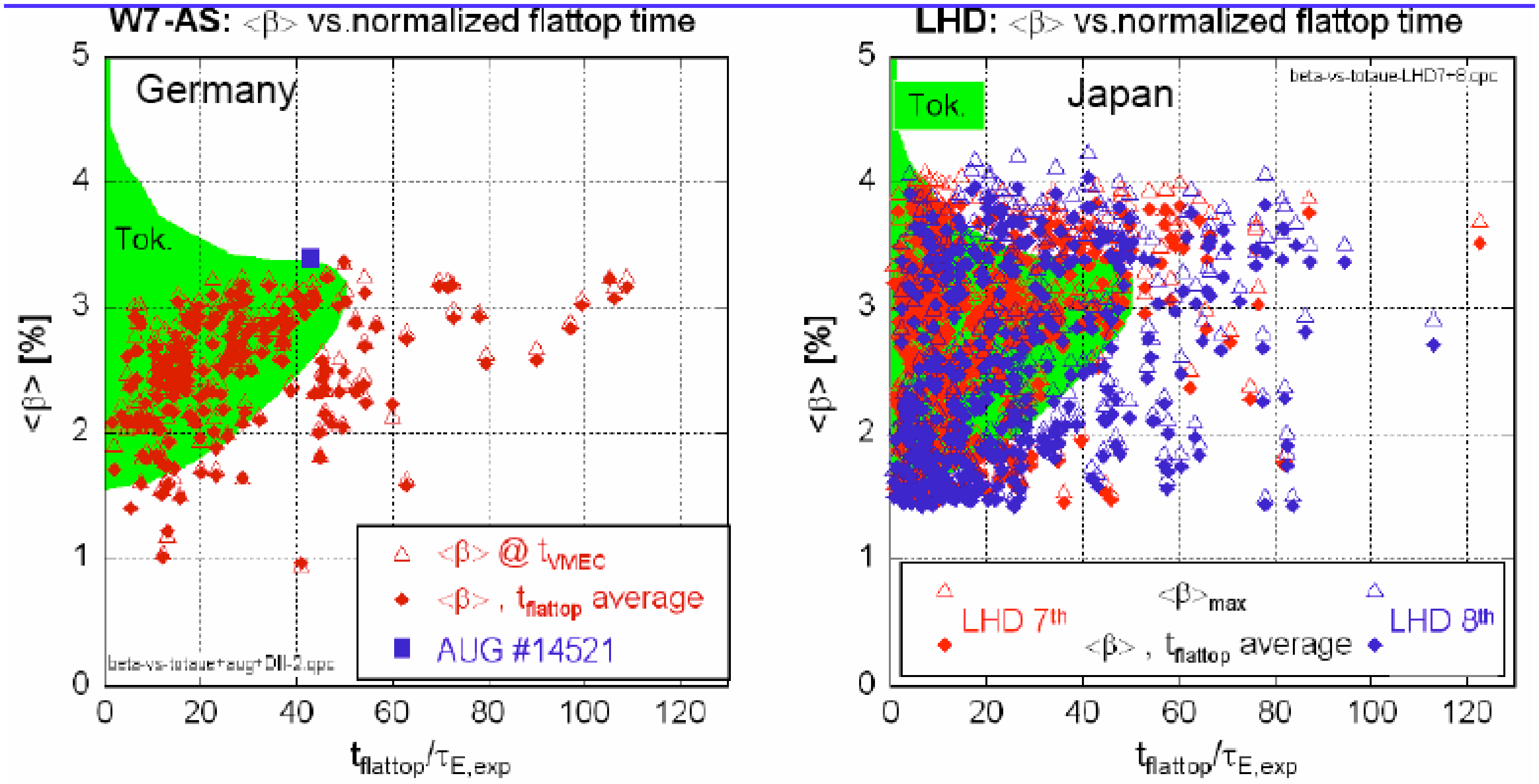




Stability limit can be so soft that an operational limit is not defined.

Robust plasma stability

Evidence (maintenance of beta)



Beta once obtained can be maintained.

Control and maintenance of the q profile without current drive

Importance

In a high-gain fusion plasma, α heating and the radial scaling of transport coefficients determine the profiles:

produces uncertainty in the magnitude of the bootstrap current.

No more than $\approx$20% of the transform $\iota=1/q$ in DEMO can be produced by current drive [ITER team, NF 47, S404(2007)]. Steady-state ITER will have about 50% driven current.

In any case, multi-month current-drive systems are challenging.

Reversed shear profiles, $j_{bs}dq/dr<0$:

stabilize neo-classical tearing (a major ITER and DEMO issue) and other instabilities.

Evidence

A vacuum rotational transform $\iota(r)\propto(\delta B)^2$ is produced by non-axisymmetric shaping. Demonstrated in fifty years of experiments.

Broad range of operating densities

Importance

DEMO discussed by ITER team [NF 47, S404(2007)] at Greenwald limit with $T_i(0)$=45kev.

Higher density-lower temperature fusion plasmas:

a. reduce pressure of α's and drive for Alfvénic instability.

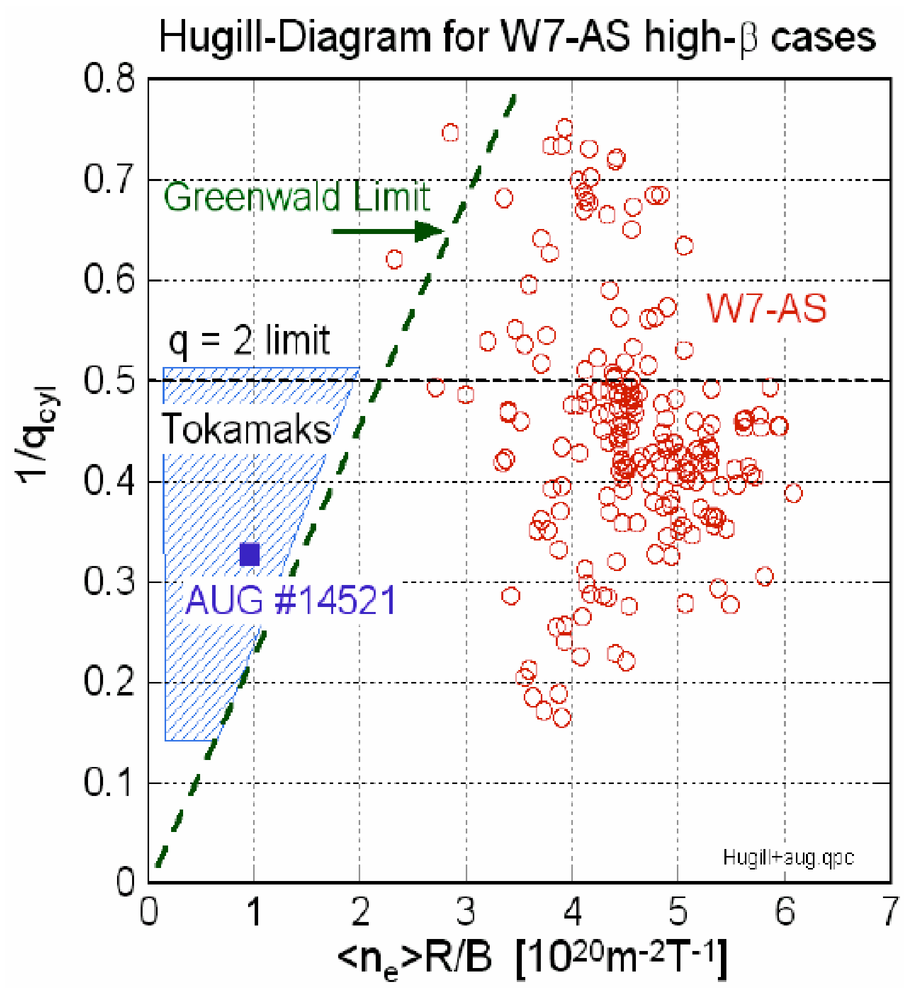
b. make divertor problem simpler by lowering the energy per particle that strikes plates, which reduces erosion.

c. reduce sensitivity to particle trajectory deviations.

Operation at densities above Greenwald limit would reduce other risks on path to DEMO.

Broad range of operating densities

Evidence (high density)



II. Important Constraints on Non-axisymmetric Shaping

1. Good magnetic surfaces

2. Particle trajectories that remain close to magnetic surfaces

3. Practical coils and structures

4. Compact (low aspect ratio) shape

Good magnetic surfaces

Error fields in stellarators degrade confinement rather than causing disruptions (locked modes of tokamaks).

Required construction accuracy is no greater than in tokamaks.

ITER team noted error fields in tokamaks, $\delta B/B$ as small as 10^{-4} can cause mode locking and disruptions [NF 47, S128 (2007)].

Resonant non-axisymmetric fields can destroy magnetic surfaces in square-root order, $(\delta B)^{1/2}$.

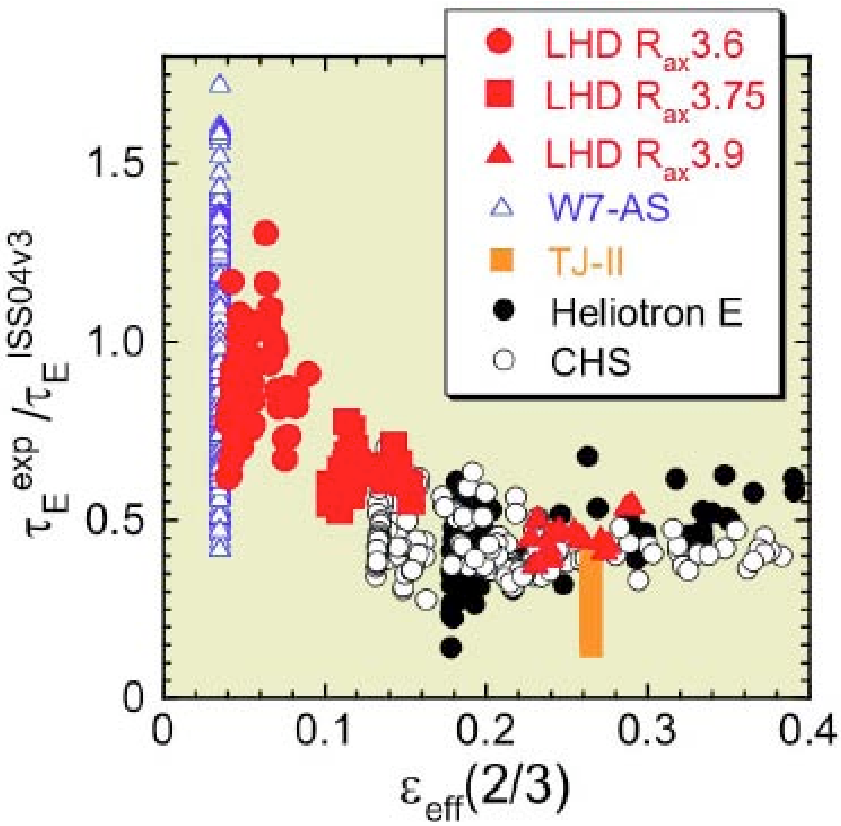
Breakup of surfaces by magnetic fields that have the toroidal periodicity N_p relatively easily controlled if the transform per period $\iota/N_p<0.25$, which becomes a design constraint.

Techniques developed for stellarators, when used to study the response DIII-D and NSTX, have explained paradoxical results and clarified methods for controlling error fields.

Particle trajectories that remain close to magnetic surfaces

Importance

Required for good α and neoclassical confinement; reduces microturbulent transport.



Particle trajectories remain close to magnetic surfaces if $|\vec{B}|$ has one of three possible symmetries: (1) toroidal, (2) poloidal, or (3) helical.

The deviation of particle drift trajectories is determined by the magnetic field strength—the geometric shape of the magnetic surfaces has no direct relevance.

Quasi-symmetry means $|\vec{B}|$ approximates a symmetry, but the shape of the magnetic surfaces does not.

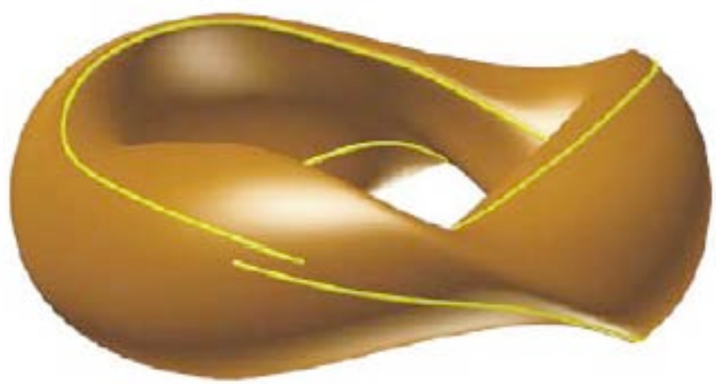
Quasi-Axisymmetry (QA)

means |B| has toroidal symmetry.

Quasi-axisymmetry can be imposed at any level of non-axisymmetric shaping of the magnetic surfaces:

From zero, the conventional tokamak.

To sufficiently large that the rotational transform is predominately produced by the shaping rather than by the plasma current.



NCSX with $\Delta\iota_{vac}/\iota$ = 75%
Only QA stellarator in world program

Quasi-axisymmetric shaping can be viewed as an extension from axisymmetric shaping to enhance the performance of tokamaks.

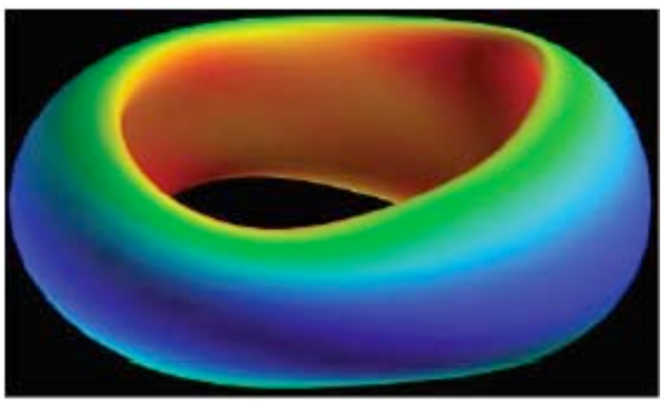
Even 1% quasi-axisymmetric shaping may be important by allowing ELM control with distant coils.

$\Delta\iota_{vac}/\iota \approx 20\%$ can:

improve stability.

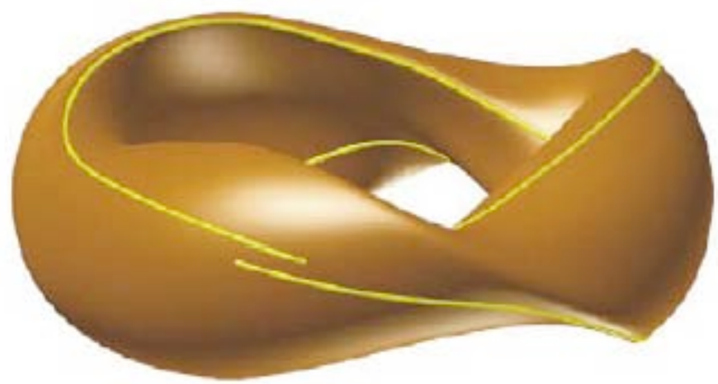
remove need for current drive.

$\Delta\iota_{vac}/\iota < 75\%$ should provide full benefits of quasi-axisymmetric shaping.



ARIES-RS but $\Delta\iota_{vac}/\iota = 20\%$

(L-P. Ku through a Columbia grant)



NCSX with $\Delta\iota_{vac}/\iota = 75\%$

Offers a smooth connection to the tokamak data base.

Quasi-Poloidal Symmetry (QP)

means |B| approximates symmetry in the poloidal direction.

In exact quasi-poloidal symmetry,

Pfirsch-Schlüter and the bootstrap currents would be zero.

Shape of magnetic surfaces and safety factor would be determined purely by the externally produced magnetic field--no dependence on the plasma pressure.

Particle drift trajectories would not leave magnetic surfaces.

Quasi-poloidal symmetry requires greater deviations from perfect quasi-symmetry than quasi-helical or quasi-axisymmetry.

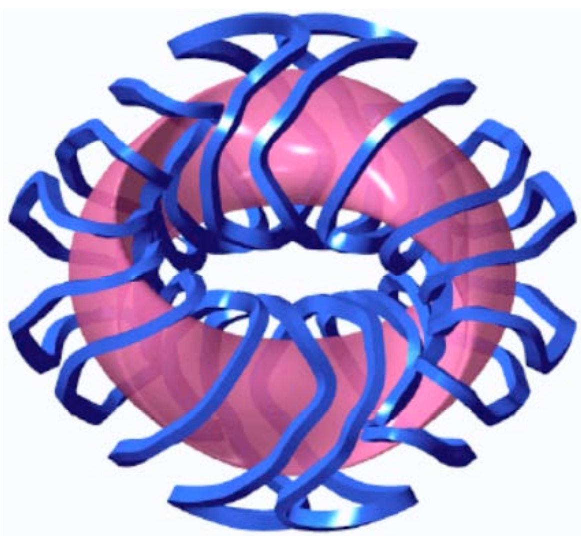
Nevertheless, toroidal equilibria can be found that approximate attractive features of quasi-poloidal symmetry.

Accomplished by minimizing the deviation of the action contours $J=\int v_{||}dl$ from the magnetic surfaces to ensure good particle confinement—called the isodynamic constraint.

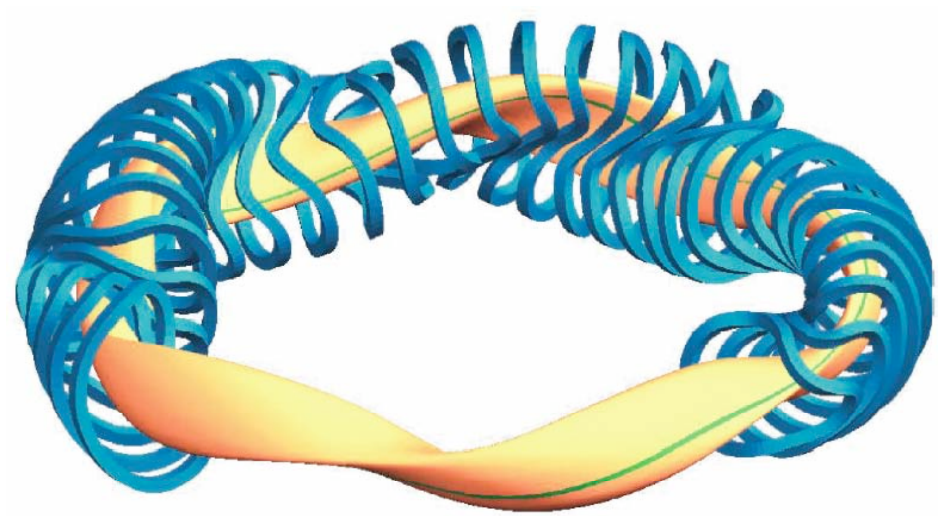
QP stellarators can be optimized over:

A broad range of aspect ratios.
Differing levels of parallel currents.
Differing rates of flowing damping.

The bulk of the trapped particles are typically in a good curvature region—unlike the situation in other toroidal devices.



QPS at Oak Ridge
Reduced flow damping



W7-X in Germany
Reduced parallel currents

Quasi-Helical Symmetry (QH)

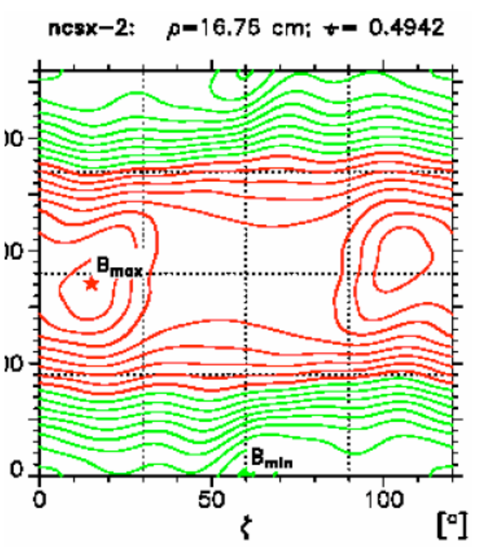
means |B| has symmetry in the helical direction.

Within the magnetic surface |*B*| is a function of $\theta_h = \theta + N_p \varphi$ alone, where N_p is the number of toroidal periods of the stellarator.

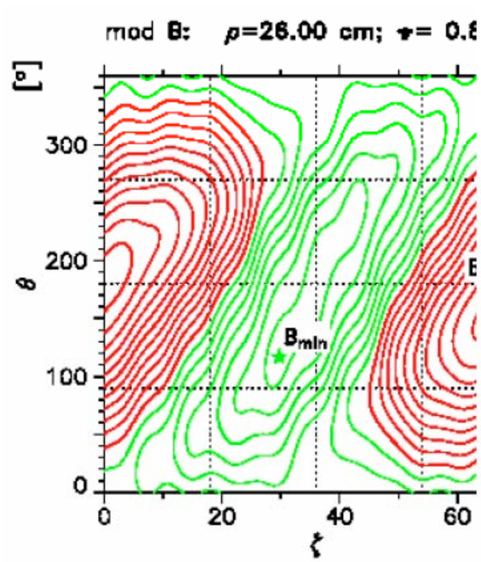
Theoretically a stellarator with helically symmetric magnetic surfaces has stable equilibria at high beta with excellent particle trajectory confinement and with a large effective rotational transform $\iota_{eff} = N_p - \iota$.

Perfect helical symmetry cannot exist at finite aspect ratio, but quasi-helically symmetric stellarators do. Optimization increasingly difficult below an aspect ratio of roughly five.

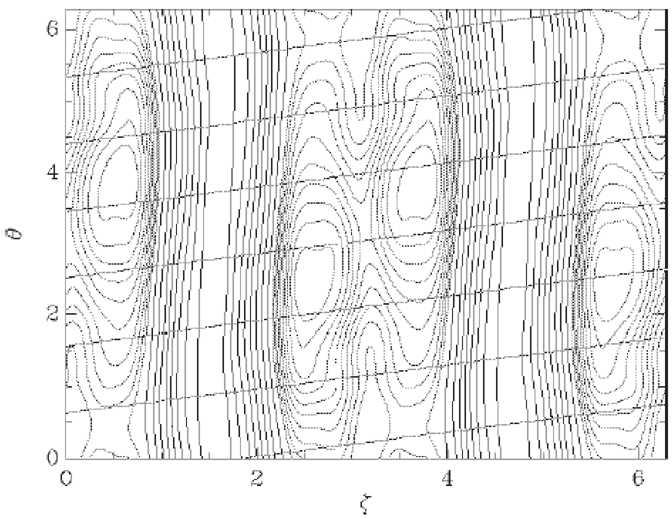
Magnetic Field Strength Plots



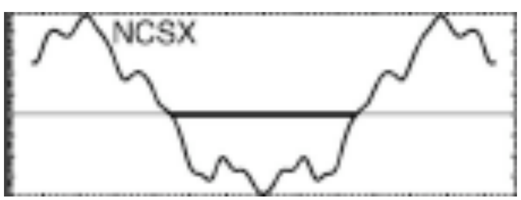
NCSX

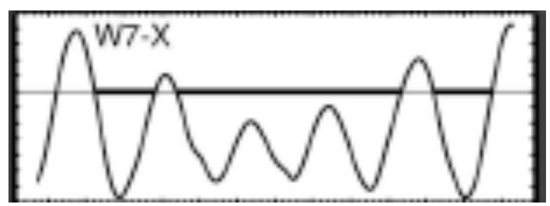


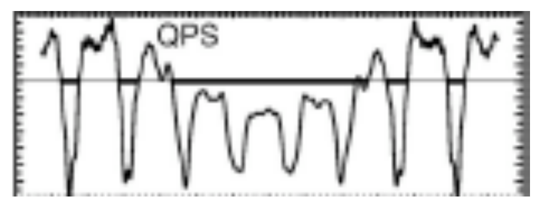
W7-X



QPS







$B(\ell)$ plots

Practical coils and structures

Construction difficulties of NCSX and W7-X may in large part be addressed by experience.

Simplified coil and structure solutions are needed to have a realistic assessment of the implications of non-axisymmetric shaping on device complexity and cost. (Research discussed below.)

Compact Shape

Compactness (low aspect ratio) reduces:

development costs

minimal size of a power plant

but is not otherwise a requirement on fusion systems.

Unlike tokamaks, stellarators are easier to design at larger aspect ratio for a given plasma performance (such as the beta limit).

If compactness is desired, it must be imposed as a constraint.

II. Research on Utility of Non-Axisymmetric Shaping

1. Transport

2. Plasma Stability

3. Density Limits

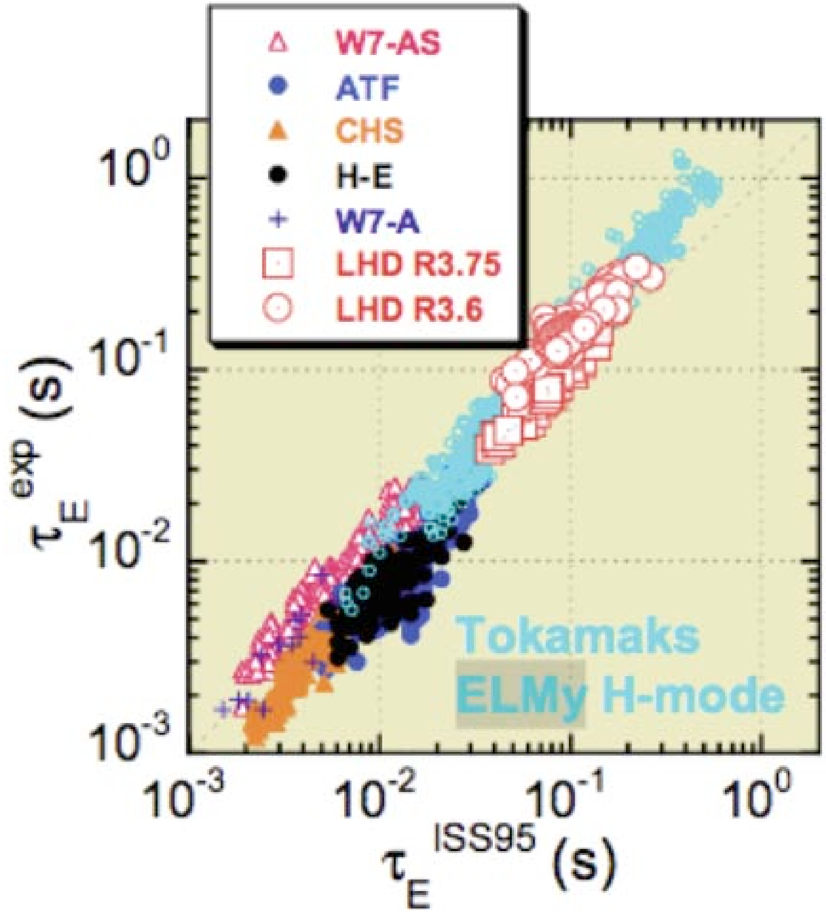
4. Energetic Particle Behavior

5. Plasma Edge and Divertors

6. Simplified Coils and Structures

Transport

Overall is similar to tokamaks.



Stellarators have flexibility to change local magnetic shear, modify damping of zonal flows, and even place trapped particles in good curvature (QP), not bad (tokamak, QA, QHS).

Profile consistency (rigid profiles) and isotope dependence not as prominent in stellarator experiments as in tokamaks--reason is not understood.

Plasma Stability

The level and type of non-axisymmetric shaping needed to avoid disruptions need better determination.

The vacuum magnetic surfaces of a stellarator define a preferred location within the vacuum chamber for the plasma—they create a plasma cage.

This topic is the focus CTH stellarator at Auburn.

The soft beta and other operational limits of stellarators need to be better understood as well as the implications for non-axisymmetric design.

Ideal MHD stability limits can often be exceeded in stellarator experiments even though some MHD activity often occurs.

Density Limits

Upper limit on density in tokamaks, the Greenwald limit, is not understood, but places difficult constraints on DEMO design.

Need to understand the level and type of non-axisymmetric shaping required for circumventing the Greenwald limit.

Energetic Particle Behavior

Transport of α's by Alfvénic instabilities in non-axisymmetric systems requires study.

Lower temperature reduces β_α and drive for instability.

Less constraining methods of confining α trajectories could simplify designs.

Examples are better minimization of action deviations and use of self-symmetrization of the plasma.

Plasma Edge and Divertors

Characterize cross-field transport of particles and heat.

ELM control through symmetry breaking at the edge of DIII-D shows that much remains to be learned about asymmetric divertors.

Compare experiments with detailed 3-D models of plasma edge.

Determine whether radiation could be used to reduce power load.

Divertors in stellarators:

Can have a long connection length.

Can operate at high density and low temperature.

Simplified Coils and Structures

Need to understand which $\vec{B}_{ext} \cdot \hat{n}$ distributions on plasma surface degrade plasma performance and must be controlled by coils and which are irrelevant, which allows coil simplifications.

An understudied topic on both tokamak and stellarators is the plasma response to magnetic perturbations.

IV. Elements of the Research Program

A timely and efficient program requires:

1. Theory

2. Design Activity

3. Experiments

Theory Research

Non-axisymmetric magnetic fields require subtle (not necessarily complicated) theory—true for stellarators and for tokamak error-field effects.

Theory allows use of data from all stellarator and tokamak experiments to predict the performance of new configurations.

> Particularly important for stellarators: Tokamaks have only about five degrees of shaping freedom (aspect ratio, ellipticity, triangularity, and squareness); stellarators have about fifty.

Drive for theory is a major issue.

> U.S. theory has been of critical importance to the world stellarator effort—the primary U.S. contribution to stellarator research.
>
> U.S. theory activity was intense during design periods (Heliac, ATF, NCSX, and QPS), but degenerated to a low level once these activities were completed.

Design Activity

Greatly extended design space of non-axisymmetric systems means ongoing design work is needed.

Coils have two purposes (a) provide toroidal magnetic flux and (b) make $\vec{B} \cdot \hat{n} = 0$ on the plasma surface. Need to determine with plasma physics input:

a. What part of the field should be produced by modular (shaped toroidal field) coils versus windowpane coils?
b. Which distributions of $\vec{B}_{ext} \cdot \hat{n}$ are needed for the required physics properties? Other distributions can be chosen to simplify coils.
c. How accurately must the machine be built? What trim coils should be used?

Engineering of:

a. Simpler vessels.
b. New strategies for distributing loads.
c. Assembly techniques.
d. Better methods for maintaining tolerances.

As our knowledge increases, design activities will be needed for planning research on non-axisymmetric shaping:

a. What levels of QA shaping are expected to give which benefits?

b. What choices with QP and QH are available at low aspect ratio?

c. What experimental tests would best verify that the critical DEMO issues have been addressed?

Experiments

Experiments of a certain scale are required to establish the utility of non-axisymmetric shaping for risk mitigation on the path to DEMO:

The larger the experiment—the lower the extrapolation risk.

World program has a dearth of operating stellarators:

One large operating stellarator: LHD in Japan

Neither compact nor optimized for good particle trajectories. Can operate in an improved trajectory configuration—reduces microturbulence.

One large stellarator under construction: W7-X in Germany

Not compact but will study benefits of good particle trajectories.

One operating quasi-symmetric stellarator: HSX at Univ. of Wisconsin

Not compact and on a scale at which neutral penetration is an issue.

CTH at Auburn University is studying stability at various levels of ι_{vac}/ι. Compact but not quasi-symmetric; at a similar scale as HSX.

No compact quasi-symmetric stellarator is in operation, but:

NCSX is in construction at PPPL.

Integrated test of issues (transport, stability, divertors, etc.) for quasi-axisymmetry.

QPS is in prototype development at ORNL.

Targets specific, rather than integrated, issues for quasi-poloidal symmetry.

If non-axisymmetric shaping is to be considered for the mitigation of risks along the path to DEMO, a program of a certain scale is required.

V. Scientific Issues Summary

The need to reduce the physics risks of the path from ITER to DEMO defines a time scale and a level of research on stellarators.

A timely and efficient program to reduce these risks requires (a) theory, (b) engineering design, and (c) major experiments.

a. What unique issues can be addressed independent of the potential for a reactor concept?

Effects of non-axisymmetry on:

Transport physics (profile rigidity, isotope effect)
Operational limits (beta and density)
Divertor physics and ELM control
Energetic particle physics

Plasma interaction with magnetic perturbations (intended or error fields).

Insights into issues of coil design and control of tolerances.

b. Advantages and disadvantages of the quasi-symmetric stellarator as a fusion system

i. Advantages

Possibility of circumventing issues that would increase the risk of DEMO while maintainging tokamak like confinement.

1. Robust stability, even at operating limits (no disruptions).
2. Steady state without current drive or feedback.
3. High density operation.

Quasi-axisymmetric shaping connects smoothly to tokamaks and may offer important benefits even at a low level.

ii. Disadvantages

More challenging engineering for acceptable coils and structures.

C. Issues needing resolution

1. Level and type of non-axisymmetric shaping required for achieving the various benefits.
2. Definition of coils and structures to provide a reliable basis for assessing device complexity and cost.