Non-Axisymmetric Shaping as a Research Thrust

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A ReNeW research thrust on non-axisymmetric plasma shaping could:

1. Provide the knowledge required to circumvent fundamental constraints of axisymmetric plasmas.

2. Exploit strengths of the U.S program to**:**

Provide world leadership in an area that may be required to go from ITER to a demonstration of fusion power (DEMO).

Costs consistent with the size of the existing U.S. fusion program.

Since no device is precisely axisymmetric,

Knowledge of non-axisymmetric shaping is required.

The issue is the optimal level and type.

Two statements of physics underlie the importance of shaping.

1. The plasma pressure and current distributions are largely self-determined in a burning plasma.

Only other determinant of plasma equilibria is the plasma shape.

Shaping is the primary design freedom to ensure a suitable plasma equilibrium for fusion.

Most of the freedom of shaping is in non-axisymmetric shaping.

2. The magnetic field strength is quasi-symmetric if $B(l+L)=B(l)$, l is distance along a magnetic field line and L is a constant on each line.

Particle drift trajectories in quasi-symmetry have the same properties as in axisymmetry.

No fundamental demarcation exists between axisymmetric tokamaks and non-axisymmetric tokamaks that are quasi-axisymmetric.

Non-axisymmetric shaping of tokamaks may be required to:

1. **Maintain the magnetic configuration.**
2. **Form a cage around the plasma making it robust against disruptions.**
3. **Relieve restrictive limits on the plasma density.**
4. **Allow a large ratio between the central and edge plasma temperature while maintaining good confinement.**

Quasi-axisymmetry has not been studied experimentally.

Benefits of non-axisymmetric shaping have been demonstrated in a number of stellarator experiments.

Benefits of the quasi-helical type of quasi-symmetry have been demonstrated in the HSX experiment.

9 of the 15 gaps cited in the 2007 FESAC report "*Priorities, Gaps and Opportunities*" can be addressed, at least in part, through research on non-axisymmetric fusion systems:

Gap 1: "***Sufficient understanding*** *of all areas of the underlying plasma physics* ***to predict the performance and optimize the design and operation of future devices***."

The design can only be optimized if the plasma response is known to the externally controllable parameters, such as plasma shape parameters.

Codes exist that select the plasma shape that optimizes any set of properties that can be calculated.

Properties that can be optimized:

1. plasma stability.
2. robustness of the plasma against striking chamber walls.
3. confinement of alpha particles.
4. fraction of the poloidal field produced by shaping.

Gap 2: "*Demonstration of integrated, steady-state, high-performance (advanced) burning plasmas, including first wall and divertor interactions.* ***The main challenge is combining high fusion gain with the strategies needed for steady-state operation***."

The DEMO discussed in the 2007 *Progress in the ITER Physics Basis* had 80% of the current from the bootstrap current.

Implies a strong self-organized coupled state between the microturblent transport and the large-scale magnetic configuration.

ITER was not designed to demonstrate the existence of this state.

Expected (bootstrap)/(driven current) a factor of 4 too small.

A poloidal magnetic field can be produced by non-axisymmetric shaping at whatever level is required to break the coupling.

Reduces the extrapolation risk from ITER to DEMO.

Gap 3: "***Diagnostic techniques suitable for control of steady-state advanced burning plasmas*** *that are compatible with the nuclear environment of a reactor*."

An axisymmetric tokamak requires feedback systems for:

1. axisymmetric instabilities.
2. resistive wall modes.
3. neoclassical tearing modes.
4. probably for the avoidance of disruptions.

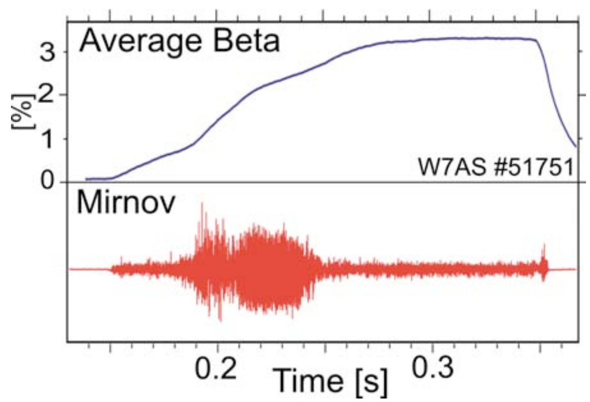
Every feedback system has a diagnostic requirement.

Plasmas with non-axisymmetric shaping can be stable without feedback, so a far lower level of diagnostic capability is required.

Gap 4: ***"Control strategies for high-performance burning plasmas, running near operating limits, with auxiliary systems providing only a small fraction of the heating power and current drive.*** *Innovative strategies will be required to implement control in high-Q burning plasma where almost all of the power and the current drive is generated by the plasma itself."*

Conundrum broken if the magnetic field is maintained without current drive by use of non-axisymmetric shaping.

The plasma pressure in stellarator experiments is not limited by catastrophic loss of equilibrium, rather by degradation in confinement. This degradation would provide benign burn control.



Gap 5: *“**Ability to predict and avoid, or detect and mitigate, off-normal plasma events** that could challenge the integrity of fusion devices*."

The plasma location in a high-performance axisymmetric tokamak is unstable and requires feedback for control.

Non-axisymmetric fields center plasma in confinement chamber.
Gives plasma robust stability against off-normal events.
such as vertical displacements and disruptions.

Importance of off-normal events involving high-energy alpha particles
(either drive or loss due to MHD activity)
largely determined by high-energy alpha density.
At a given fusion power density scales as $T^{5/2}$.

Density of high-energy alphas is more than an order of magnitude lower in stellarator designs for fusion systems than for tokamak.

Gap 6: "***Sufficient understanding of alternative magnetic configurations that have the ability to operate in steady-state without off-normal plasma events****. These must demonstrate, through theory and experiment, that they can meet the performance requirements to extrapolate to a reactor and that they are free from off-normal events or other phenomena that would lower their availability or suitability for fusion power applications*."

Stellarators are the standard example of such a system.

Gap a statement of concern about alternatives to non-axisymetric shaping.

Gap 7: "***Integrated understanding of RF*** *launching structures and wave coupling for scenarios suitable* ***for Demo*** *and compatible with the nuclear and plasma environment*."

The requirements for these systems are greatly reduced if no steady-state power is required to drive the plasma current.

Gap 9: ***"Sufficient understanding of all plasma-wall interactions*** *necessary to predict the environment for, and behavior of, plasma facing and other internal components for Demo conditions."*

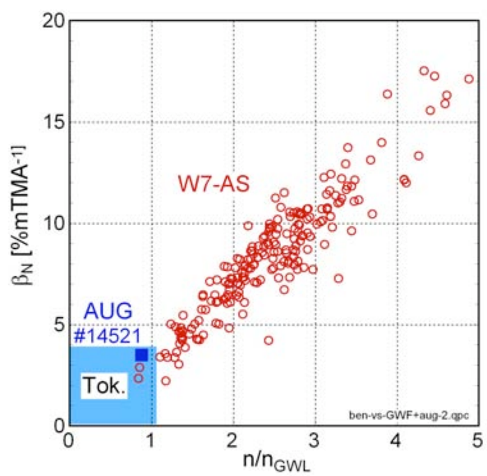
A high density, low temperature plasma edge would partially address.

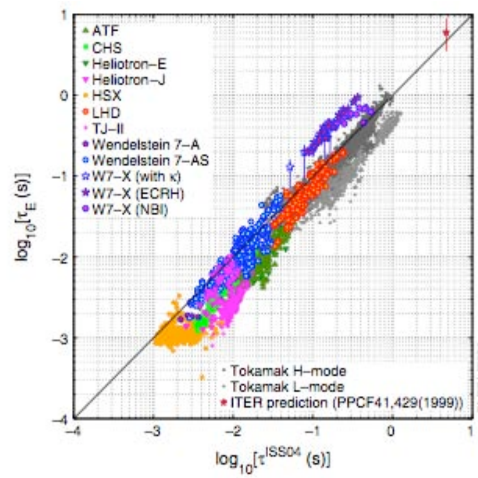
Tokamak density limits: Greenwald & current drive efficiency.

Stellarators can operate at a far higher density than tokamaks.

At a given fusion power density means a far lower temperature.

Good confinement appears possible in stellarators with a larger ratio of the central to the edge temperature than in tokamaks.

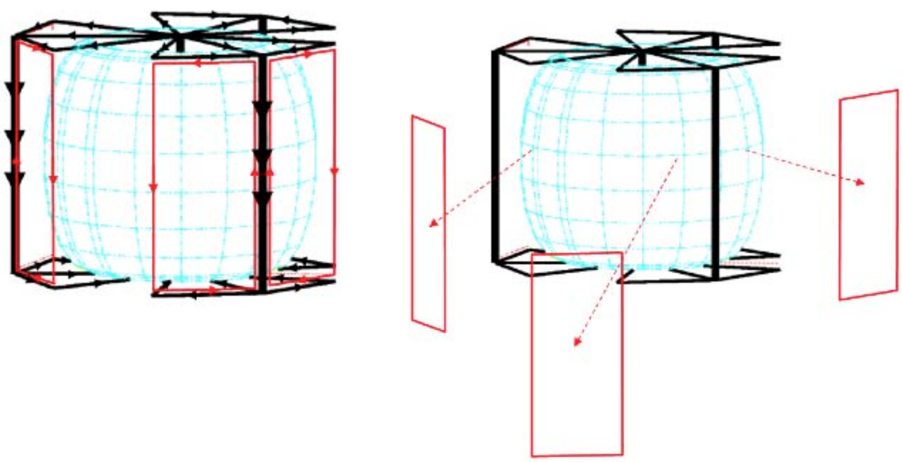




Gap 15: *"The knowledge base for* ***efficient maintainability of in-vessel components*** *to guarantee the availability goals of Demo are achievable."*

Access to the plasma chamber for maintenance is an important aspect of this issue.

By thinking of coils as three-dimensional systems, chamber access can be optimized even in an axisymmetric tokamak.



A high density, low temperature plasma edge would aid by placing less stress on the in-vessel components.

**Unless a credible alternative is known for closing each gap,
non-axisymmetric shaping may be essential.**

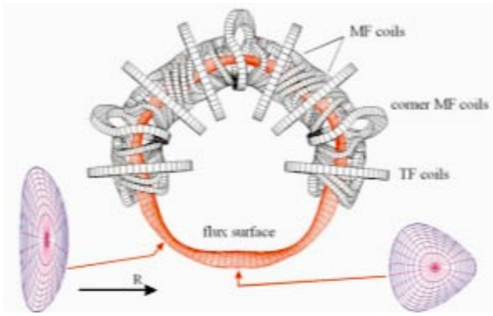
Gap 6 expresses concern about the existence of alternatives.

The removal of the artificial design constraint of axisymmetry on the tokamak path from ITER to DEMO cannot diminish the probability of success.

Where known alternatives exist to non-axisymmetric shaping

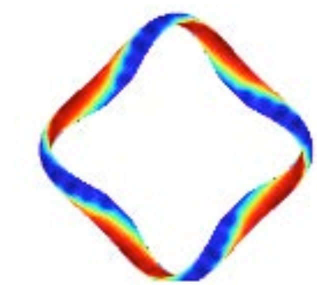
Comparisons are required to develop
fusion power with minimum cost, time, and uncertainty.

Important features demonstrated in stellarator experiments.



W7-AS (0.18m/2m, 2.6T)

LHD (0.6m/3.6m, 3T)



HSX(0.15m/1.2m, 1.3T)

A major hole exists in the world and domestic fusion programs that are focused on ITER.

No program of experiments and theory exists to explore benefits of tokamak shaping with non-axisymmetric fields for $\delta B/B > 10^{-3}$.

Targeted research needed to determine level of non-axisymmetric shaping required to:

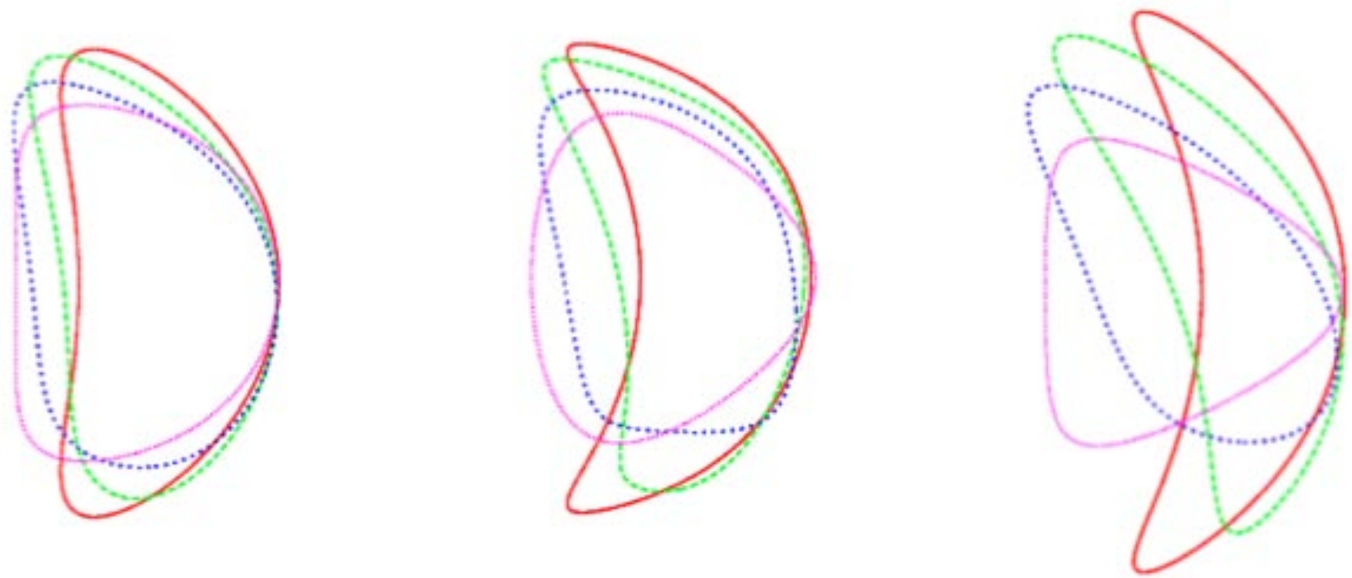
1. Avoid disruptions and Greenwald density limit.
2. Allow a high center/edge temperature ratio.
3. Maintain magnetic configuration without current drive.

An experimental program to explore benefits of non-axisymmetric shaping requires a low-collisionality, high-beta plasma.

Implies a program cost of at least 40 M$/year.

Strong theory and engineering programs would also be required.

Could add 10 M$/year to the overall program costs.



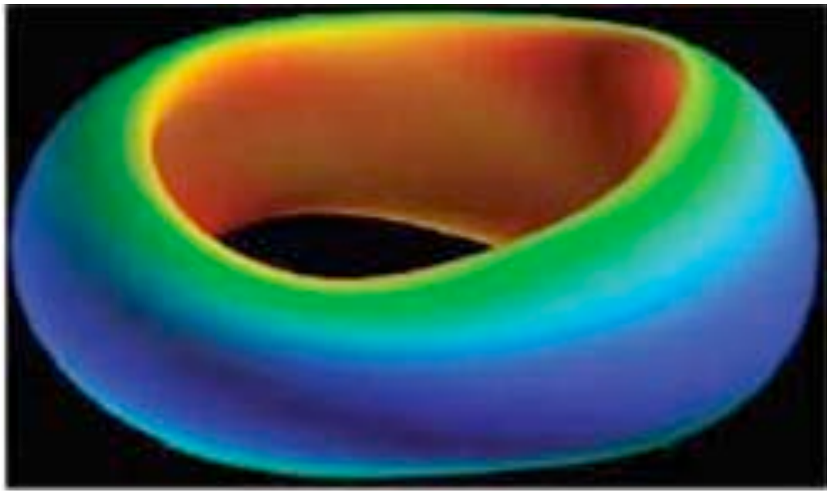
Long-Poe Ku

$\iota_{ext}=0.045$	$\iota_{ext}=0.09$	$\iota_{ext}=0.27$
$\iota_{ext}/\ \iota_{edge}=18\%$	$\iota_{ext}/\ \iota_{edge}=37\%$	$\iota_{ext}/\ \iota_{edge}=60\%$
(Vertical stability)	(No current drive/caged from walls)	(No RWM)

All quasi-axisymmetric, $\langle\beta\rangle=4\%$, $A=4$, three field periods.

Expertise on quasi-axisymmetric shaping would give US unique capabilities in exploiting ITER information to make fusion a reality.

For maximal utility, the expertise should be developed by the time the ITER information becomes available.

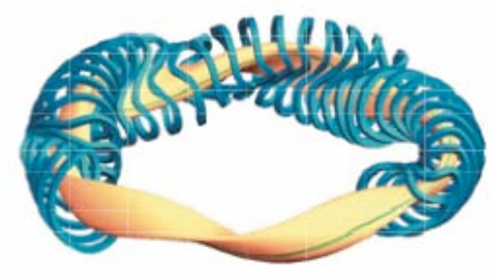


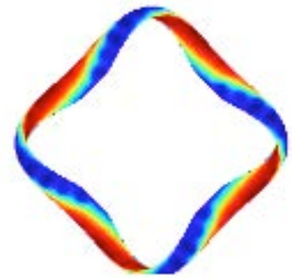
ARIES-RS but ι_{vac}/ι=20%

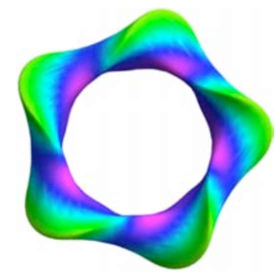
Non-axisymmetric shaping is more general than quasi-symmetry.

Neither LHD (Japan) nor the W7-X (Germany) is quasi-symmetric.


LHD


W7-X


HSX


CTH

Both have features not possible in quasi-symmetry.

W7-X has $j_{||} \approx 0$; magnetic configuration almost independent of p.

Both offer important platforms for U.S. collaborations.

HSX (Wisconsin) has demonstrated importance of quasi-symmetry $B(l)=B(l+L)$ and is exploring the benefits of quasi-helical symmetry.

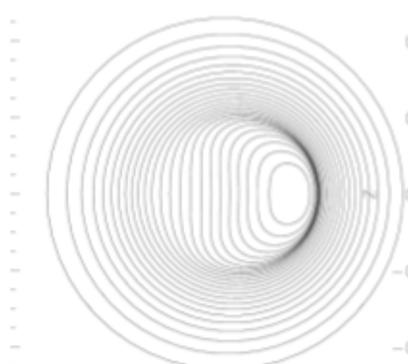
CTH (Auburn) is exploring disruption avoidance in systems with non-axisymmetric shaping and a net plasma current.

Non-axisymmetric shaping has importance beyond tokamaks and stellarators.

Reversed Field Pinch (RFP) is an example.

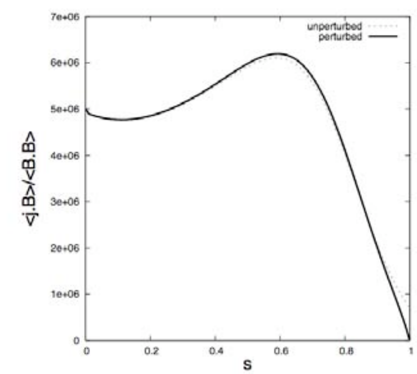
RFP experiments have shown much improved confinement when the magnetic axis follows a helical path around the torus.

Proposed to add helical shaping to eliminate need for magnetic relaxation events.



Helical Axis (VMEC)

Neil Pomphrey



Helical Shaping (VMEC)

Experiments underway on both concepts on the RFX device (Italy) with a U.S. theory collaboration based on VMEC calculations.

Non-axisymmetric shaping has a reputation of complexity and axisymmetry of simplicity.

Non-axisymmetric coils and chambers may be difficult to design.

But, the axisymmetric tokamak has a requirement for:

1. Feedback of: (a) axisymetric vertical instability,
   (b) the resistive wall mode, and
   (c) neoclassical tearing mode.
2. Quick discharge termination if a disruption is imminent.
3. Steady-state current drive systems.

By comparison, a passively stable, steady state, non-axisymmetric plasma may seem simple indeed.

No device is precisely axisymmetric.

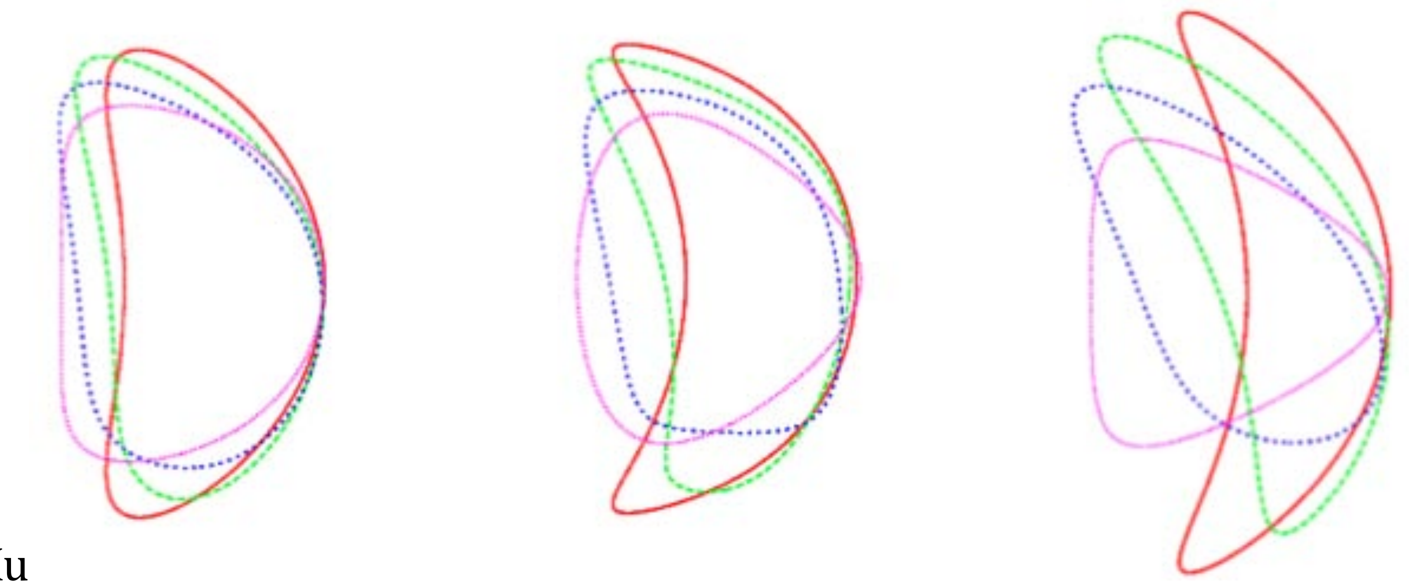
Experimental and theoretical research on the physics of non-axisymmetric shaping must be targeted.

Research shouldn't ignore benefits of non-axisymmetric shaping.

Further discussion of non-axisymmetric shaping with references:

Stellarators and the path from ITER to DEMO
A. H. Boozer
Plasma Phys. Control. Fusion **50**, 124005 (2008).

Use of non-axisymmetric shaping in magnetic fusion
A. H. Boozer
Phys. Plasmas (May 2009)



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