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 and (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). The potential benefits are enormous, but the costs are consistent with the size of the existing U.S. fusion program. No device can be precisely axisymmetric, so knowledge of the effects of non-axisymmetric shaping is required. The issue is the optimal level and type of shaping.

Two statements of physics underlie the importance of non-axisymmetric shaping. (1) The plasma pressure and current distributions are largely self-determined in a burning plasma, and the only other determinant of a plasma equilibrium is the plasma shape. Consequently 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 $B(l+L)=B(l)$, where l is the distance along a magnetic field line and L is a constant on each line. The 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, 2]: (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, and (4) allow a large ratio between the central and edge plasma temperature while maintaining good confinement. Although quasi-axisymmetry has not been studied experimentally, the benefits of non-axisymmetric shaping have been demonstrated in a number of stellarator experiments, and the benefits of the quasi-helical type of quasi-symmetry has been demonstrated in the HSX experiment.

The October 2007 report to the Fusion Energy Sciences Advisory Committee (FESAC) on the "*Priorities, Gaps and Opportunities: Towards A Long-Range Strategic Plan For Magnetic Fusion Energy*" cited fifteen gaps in the required knowledge for a demonstration of fusion power (DEMO). Nine of these gaps can be addressed, at least in part, by research on non-axisymmetric fusion systems [2]. These are:

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. Examples are the plasma stability, the robustness of the plasma against striking the chamber walls, the confinement of alpha particles, and the 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* [3] had eighty percent of the current from the bootstrap current. This 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, and the ratio of the bootstrap to the driven current is expected to be a factor of four too small to do so [3]. A poloidal magnetic field can be produced by non-axisymmetric shaping at whatever level is required to break this coupling and reduce 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 axisymmetric instabilities, resistive wall modes, neoclassical tearing modes, and probably for the avoidance of disruptions. Each feedback system has diagnostic requirements. 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*." The magnetic field can be maintained without current drive by use of non-axisymmetric shaping, which breaks the conundrum cited in this gap. The plasma pressure in stellarator experiments is not limited by catastrophic loss of equilibrium, rather by degradation in confinement. The 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 tend to center the plasma in the confinement chamber, which gives the plasma robust stability against off-normal events such as vertical displacements and disruptions. The importance of off-normal events that involve a drive by, or the loss of, the high-energy alpha particles is largely determined by their density, which at a given fusion power density scales as $T^{5/2}$. The density of high-energy alpha particles 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 a system that may achieve these goals.

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 the concerns associated with this issue. The plasma density in tokamaks is limited by (1) the Greenwald density limit and (2) the efficiency of current drive. Stellarators with strong non-axisymmetric shaping can operate at a far higher density than tokamaks, which 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 of these gaps, non-axisymmetric shaping may be essential. Gap 6 is in essence a statement of concern about the existence of alternatives. The removal of the artificial design constraint of axisymmetry [1, 2] on the tokamak path from ITER to DEMO cannot diminish the probability of success. Where known alternatives exist to non-axisymmetric shaping, a comparison should be made, so fusion power can be developed with minimum cost, time, and uncertainty.

Many of the important features of non-axisymmetric shaping have been demonstrated in stellarator experiments. However, a major hole exists in the world and the domestic fusion programs, which are focused on the ITER tokamak. No program of experiments and theory exists to explore the benefits of tokamak shaping augmented with non-axisymmetric fields with $\delta B/B>1/1000$. Without targeted research, the magnitude of the non-axisymetric shaping that is required to avoid issues, such as tokamak disruptions or the Greenwald density limit, will remain unknown.

An experimental program to explore the benefits of non-axisymmetric shaping requires a low-collisionality, high-beta plasma, which implies a program cost of at least 40 M$/year. Strong theory and engineering programs would also be required, which could add 10 M$/year to the overall program costs. A much larger program could be justified by the importance of non-axisymmetric shaping to the success of fusion.

Expertise on quasi-axisymmetric shaping would give the US unique capabilities in exploiting the information from ITER to make fusion a reality. For maximal utility, the expertise should be developed by the time the ITER information becomes available.

Non-axisymmetric shaping is more general than quasi-symmetry. Neither the LHD stellarator in Japan nor the W7-X stellarator being built in Germany is quasi-symmetric. Both have features not possible in quasi-symmetry. For example, W7-X has essentially no plasma current parallel to the magnetic field lines, which makes the magnetic configuration essentially independent of the plasma pressure. Both stellarators offer important platforms for U.S. collaborations for extending the knowledge of non-axisymmetric shaping. The much smaller HSX stellarator at the University of Wisconsin has demonstrated the importance of quasi-symmetry and is exploring the benefits of quasi-helical symmetry. The CTH stellarator at Auburn University is exploring disruption avoidance in systems with non-axisymmetric shaping and a net plasma current.

Non-axisymmetric shaping has importance beyond tokamaks and stellarators. An example is the reversed field pinch (RFP). RFP experiments have shown much improved confinement when the magnetic axis follows a helical path around the torus, and it has been proposed to add helical shaping to eliminate the need for magnetic relaxation events. Experiments are underway on both concepts on the RFX device at Padua, Italy with U.S collaboration.

The physics of non-axisymmetric shaping has an importance that crosses concept boundaries. Two examples are magnetic field error control and magnetic stochasticity. (1) Magnetic field errors must be controlled in all magnetic fusion concepts. As shown theoretically and in tokamak experiments, error field control is subtle since plasmas are highly sensitive to some field errors and insensitive to others. Practical error field control is not equivalent to error field reduction. (2) Magnetic stochasticity is an important issue in all toroidal magnetic fusion concepts. The electric fields that are required to maintain quasi-neutrality in a region with stochastic field lines can (1) give enhanced $E\times B$ transport and (2) change the $E\times B$ plasma rotation. Neither effect is well understood theoretically or experimentally. The change in rotation associated with stochasticity implies torques, so if the perturbation causing stochasticity is too weak to carry the required torque, shielding currents must arise in the plasma to prevent the stochasticity from occurring.

Non-axisymmetric shaping has a reputation of complexity and axisymmetry of simplicity. Although non-axisymmetric coils and chambers may be difficult to design, does that make the system more complicated than an axisymmetric tokamak? The axisymmetric tokamak has a requirement for feedback of the axisymetric vertical instability, the resistive wall mode, and the neoclassical tearing mode, for a method to quickly terminate the discharge if a disruption is imminent that could destroy the machine, and steady-state current drive systems. By comparison, a passively stable, steady state, non-axisymmetric plasma may seem simple indeed. Since no device is precisely axisymmetric, experimental and theoretical research on the physics of non-axisymmetric shaping must be targeted, and this research should not ignore the unique benefits of non-axisymmetric shaping.

[1] A. H. Boozer, Plasma Phys. Control. Fusion **50**, 124005 (2008).

[2] A. H. Boozer, *Use of non-axisymmetric shaping in magnetic fusion*, Phys. Plasmas, May 2009.

[3] Y. Gribov *et al.*, Nuclear Fusion **47**, S385 (2007).