Importance of Quasi-Axisymmetry to Achieving the Goal of ITER

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The official programmatic goal of ITER is the demonstration of *the scientific and technological feasibility of fusion power for peaceful purposes.* In Latin ITER means path–the path to the demonstration of the feasibility of fusion energy using magnetically confined plasmas. Successful pathfinders avoid impenetrable obstacles by being aware of the region they are traversing. The success of the ITER path to fusion will depend on our knowledge of the behavior of plasmas in the vicinity of that path.

The freedom in the ITER path to fusion energy lies largely in the plasma shape. Fusion power is only feasible if the energy confinement time is very long compared to the collision times, which implies that a magnetically confined plasma must be close to a scalar pressure equilibrium, $\vec{\nabla} p = \vec{j} \times \vec{B}$. Mathematics says a scalar pressure equilibrium is specified by: (1) the profile of the plasma pressure, (2) the profile of the current in the plasma, and (3) the shape of the outermost plasma surface. In a fusion plasma the profiles of the pressure and plasma driven current, the bootstrap current, are essentially determined by the balance of fusion energy production and microturbulent transport. An acceptable energy multiplication factor Q in a steady-state axisymmetric tokamak is consistent with no more than 20% of the current being externally driven. Even in a pulsed axisymmetric tokamak, the driven current must be small to have an acceptable pulse length. That is, both the pressure and the current profiles are largely self-determined in a fusion plasma, so the freedom to shape the outermost plasma surface defines much of the freedom in the path to fusion energy.

The importance of the axisymmetric shaping (aspect ratio, ellipticity, trianguarity and squareness) to the achievement of the ITER goal is understood. The axisymmetric shape parameters are about 10% of the total number that can be efficiently controlled by external coils. The others define non-axisymmetric shapes.

Limiting the path to fusion to axisymmetry requires faith–faith that plasmas naturally self-organize into a state in which the fusion power and microturblent transport combine to give the bootstrap current required for the stable maintenance of the magnetic configuration. Non-axisymmetric shaping gives the design freedom required to maintain the magnetic configuration independent of the details of the bootstrap current. In addition, non-axisymmetric fields can form an effective cage around the plasma, which gives the strong robustness against disruptions seen in stellarator experiments. Also the non-axisymmetric shaping of stellarator experiments removes restrictive upper limits on the plasma density. A low plasma density leads to strongly driven energetic particle modes and makes the divertor problem more difficult.

To have adequate energy and alpha confinement in a fusion system similar to ITER, the non-axisymmetry must be constrained by quasi-axisymmetry, which means the field strength appears essentially axisymmetric even though the plasma shape is not. In other words, most of the freedom in the ITER path to demonstrating the feasibility of fusion energy lies in quasi-axisymmetric shaping, and non-axisymmetric shaping is known to provide routes around potential obstacles in that path.

The importance of assessing quasi-axisymmetry for bypassing obstacles in the ITER path to fusion would appear manifest. However, even straightforward applications of existing computational tools to advancing this understanding are not supported, and the only experiment designed to directly study quasi-axisymmetric shaping was recently cancelled.

Is there sufficient time for the study of non-axisymmetry to affect the interpretation of the data from ITER on the feasibility of fusion power? In the official ITER schedule, it will be 14 years before $Q = 10$ plasmas will be maintained for 400 s, and 15 years before full non-inductive current drive will be demonstrated and then with a driven current fraction four times larger than is acceptable in a steady-state fusion reactor. The next 15 years should be used wisely to clarify the freedom in the ITER path, for the path defined by ITER cannot be followed to fusion power until all obstacles are addressed.

What is the appropriate research program on quasi-axisymmetry? Before the cancellation of NCSX, the U.S. planned a research program on quasi-axisymmetry of approximately 10% of its non-ITER-construction budget for fusion–about 1% of the world ITER program. Of greater relevance is the October 2007 report to the Fusion Energy Sciences Advisory Committed on *Priorities, Gaps, and Opportunities*, the Greenwald panel, which discussed a number of obstacles that lie along the ITER path to fusion energy. Methods of bypassing such obstacles must be identified to meet the ITER goal. The unique potential for bypassing physics obstacles defines a priority for research on quasi-axisymmetric shaping. What alternatives exist other than faith in the benign self-organization of axisymmetric fusion plasmas?