LETTERS TO THE EDITOR

ANOMALOUS TOKAMAK TRANSPORT AND TURBULENCE CONTROL

Substantial progress has been made in defining the engineering design for the next class of tokamak experiments [e.g., TPX and the International Thermonuclear Experimental Reactor (ITER)]. However, designs are predicated on plasma transport physics, which is "anomalous" and described by scaling laws. These scaling laws are based on careful fits to the experimental data, but have some basic difficulties, as follows:

1. The underlying (anomalous) physics is not understood.[1]

2. Large gaps exist in the multiparameter data space over which the scaling laws are fitted.[1]

3. Fusion product physics will dominate in ITER-class experiments. The scaling laws include fusion product heating as a confinement time degradation, e.g., varying as the heating (alpha particle plus auxiliary) power to some negative exponent. While this degradation is well tested (e.g., for neutral beam heating), no experiments have tested this scaling for fusion product heating. Moreover, other effects are not included in the scaling laws, e.g., confinement changes due to alpha-particle ash accumulation, thermal runaway, and alpha-particle-driven velocity space instabilities.

4. The transport "physics" for ITER-class experiments are extrapolations of the scaling laws with no certainty that the scaling(s) apply in those regimes. This is the most severe difficulty.

5. The history of tokamak experiments shows that every new class of machines finds new and unexpected physics, despite the best theoretical efforts to predict the results. There is no reason to expect that ITER-class tokamaks will be an exception to this historical rule.

Consequently, the ITER design involves a very large machine to mitigate the effects of anomalous transport. A better understanding of the physics or control of the anomalous transport is needed.

Anomalous transport is driven by plasma turbulence (chaos), which arises when a system evolves nonlinearly, causing adjacent trajectories to diverge exponentially. Recent work at the University of Maryland[2] theorized a chaos control method as judiciously applied, time-dependent (small) nudges so that orbits converge to a predetermined periodic motion. This method begins with any initial condition, waits until the trajectory lies within some desirable domain, then applies feedback control. The scheme has been demonstrated experimentally for a simple chaotic system.[3] Subsequent work has included control of chaos in the presence of noise[4] and control of transient chaos.[5] Moreover, natural examples of chaos control exist for complex, distributed systems as sketched below:

1. Asian fireflies in bushes and trees begin flashing randomly. After ~30 min, all fireflies in a tree or bush flash in unison.[6]

2. A hard, steady rain calms large, wind-blown ocean waves, apparently by quelling midsized waves, through which wind power is transferred to large waves.[7] A thin oil layer on the ocean surface has a similar effect.

3. A dolphin can swim much faster than allowed by turbulent water flow over its complex body shape, for known values of its muscular propulsive force. The swimming speed is consistent with laminar flow, apparently induced by skin oscillations.[8]

4. Birds in three-dimensional flight avoid midair collisions with other members of the flock via chaos control strategies.[9,10]

Chaos applies to all physical systems, so the methodology of Ott et al.[2] applies to fusion plasma systems. Thus, chaos control has the potential to reduce turbulent transport, improving confinement and reducing the size (and cost) of the next class of tokamaks.

The purpose of this letter is to propose control of chaos[11] as a much better methodology, as a basis for the next generation of tokamak experiments. The marvel of this method is that one simply needs to find an adequate control strategy. An understanding of the underlying chaos physics (and its control) is not required.[2] As noted above, active feedback control may be required in some cases (e.g., birds avoiding collisions). In other cases, the control strategy can be an appropriate operating domain (e.g., enough rainfall to calm wind-driven sea waves). Selection of operational regime(s) is used already (for example) to avoid major disruptions and to initiate (and maintain) the transition from L- to H-mode tokamak transport. Potential control strategies include the judicious injection (or removal) of energy, momentum, or mass via particles (or waves), as well as the imposition of static or time-varying fields (electric and magnetic). For example, biased limiter experiments have improved tokamak confinement. Is confinement better for a combination of direct current limiter bias, alternating current field component(s), and removal (or injection) of substantial current? By analogy to example 2 above, can incoherent wave injection (v = frequency, $k_\parallel$ = parallel wave number) quell turbulence (V = frequency, $K_\parallel$ = parallel wave number) with $v \gg V$ and $k_\parallel \gg K_\parallel$? If turbulent transport can be controlled with such techniques, smaller and less expensive ITER-class experiments may be possible.

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ION DEFOCUSING IN MULTICUSP PLASMA CONFINEMENT SYSTEMS

The proposed Polywell® polyhedral multicusp plasma confinement systems are designed to achieve strong ion focusing to a radius $r_c \ll R$ (Refs. 1 and 2). In this letter, a phenomenon is indicated that may tend to limit the attainable degree of focusing.

The plasma is produced by electron beam injection radially inward through the point cusps. As the electron density increases, electron diamagnetic currents push the magnetic surfaces outward, producing a relatively sharp boundary, as illustrated in Fig. 1. Ions are confined mostly by the electrostatic potential well, with only weak magnetic effects at the edge.

Since electrons can flow comparatively easily along magnetic field lines, the variation of electrostatic potential along magnetic field lines is relatively gradual. The contours of electrostatic potential tend to have shapes similar to those of the magnetic surfaces, as illustrated by the hypothetical contours of Fig. 2.

Consider the trajectories of ions that are initially well focused to within a small radius r_c at the center of the device. As these ions leave the central region, they are reflected

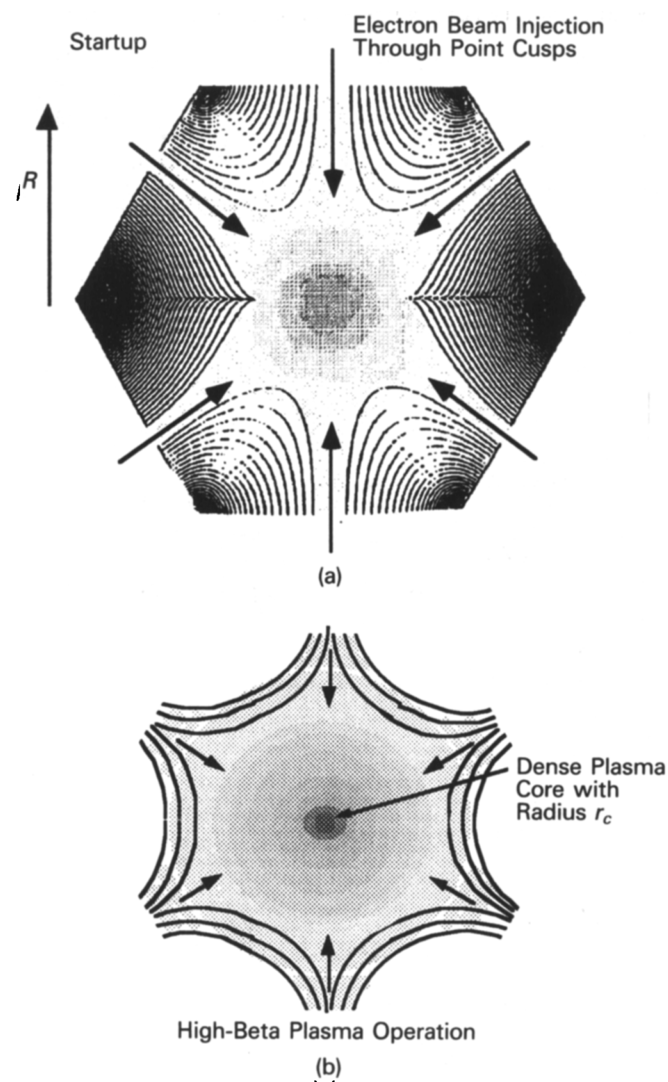

Fig. 1. (a) Startup by electron beam injection and (b) high-beta operation.