Small change in tokamak plasma shape can make big improvements in fusion performance

Recent experiments to optimize the plasma shape bring us one step closer to achieving the goal of steady-state tokamak operation for fusion energy production,

Tokamaks are donut-shaped, magnetically confined, hot plasmas that may one day be used in nuclear fusion reactors. Much of the confining magnetic field is provided by an electric current, typically on the order of 1 million Amperes, flowing in the plasma. This current is usually driven by a constantly changing current in a transformer coil threading the hole in the donut. The required current ramp imposes an inherent limitation to pulse length. Such an inductively driven tokamak fusion reactor would have to operate in pulses, possibly driving up the cost of electricity and lowering the lifetime of material components.

An alternative approach seeks to drive all of the current noninductively with injected atomic beams, injected waves, and “bootstrap” current arising naturally from charged particle trajectories in the tokamak. When these combine in the right way, they can replace the transformer without compromising confinement quality. However, achieving and sustaining this state is challenging: β, the ratio of the plasma pressure to the magnetic pressure, must be high to get the required (65% or more) bootstrap current fraction. Operating with very high β challenges known stability limits. Experiments seek to establish conditions that maximize these limits, and then operate in a controlled manner just below them.

Recently, scientists working on the DIII-D tokamak have shown that the plasma cross-sectional shape can be adjusted to optimize these components. It has long been known that warping the shape from purely circular to oval or even somewhat triangular can improve stability. Recent experiments focused on the degree to which the shape approaches a rectangle or square. The experiments show there is an optimal amount of plasma squareness: There is about a 30% difference in the maximum achievable β and about an 11% difference in energy confinement time between the best and worst squareness values (Fig. 1). The benefits of this optimal shape are not lost when the plasma is unbalanced slightly up or down to optimize particle control using cryopumped “divertors” coupled to open magnetic field lines outside the boundary.

By optimizing shape shape, the DIII-D experiment achieved significant simultaneous increases in stability, confinement, and density control. This enabled operation with roughly a doubling of the time 100% of the plasma current can be sustained noninductively, with the remaining limitations being imposed by hardware capabilities rather than the plasma itself.

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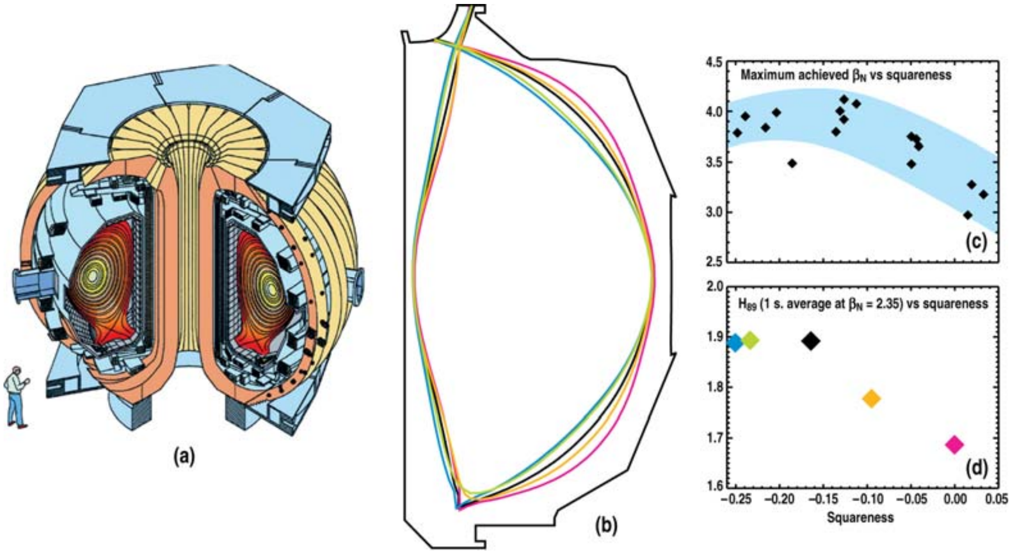

Fig. 1. (a) Drawing of the DIII-D tokamak. (b). Cross section showing the range of shapes covered in the squareness scan. (c). Maximum achieved normalized beta versus squareness. (d). Normalized energy confinement time versus squareness, color coded to match (b).