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Magnetic Confinement: Establishing the Principles through Experiment

STEWART PRAGER, University of Wisconsin - Madison

In the past fifty years, the quality of magnetic confinement (the product of density x temperature x confinement time) has increased by a factor of 100,000. Fueling this evolution is the development of robust physics principles, from single particle behavior to turbulence. These principles have evolved through experiments in many configurations, and continue to stimulate progress in plasma confinement. Early appreciation of the constraining effect of symmetry on single particle motion yielded a focus on axisymmetric tori; today, symmetry ideas appear in 3D stellarator experiments with the new ingredient of quasi-symmetry. Collecting particles into an MHD equilibrium has become routine for a wide range of plasma structures. Specially tailored equilibria are now produced by wave-driven and pressure-driven (bootstrap) currents. The principle of favorable magnetic curvature for stability has been established and exploited in many configurations; recently, high plasma pressure is obtained in the spherical tokamak by enhancement of good toroidal curvature. But plasma stability can be interrupted by magnetic reconnection events that scramble the magnetic field, forcing fusion experiments to unravel the physics of reconnection. Early experiments revealed the ubiquity of turbulence that degrades confinement. Now, turbulence is partly controlled, from electrostatic turbulence in tokamaks to magnetic turbulence in reversed field pinches. All these principles combine in the grand experiment of our era: ITER, a burning plasma with fusion-produced alpha particles confined in shaped plasma equilibria, with favorable average curvature, assisted by wave-driven and bootstrap currents, situated in turbulence reduced by flow shear. And experiments continue to advance, with no sign of saturation, the physics of tokamaks and the broad spectrum of other magnetic configurations.