Tokamak error fields minimized using an adaptive control method

Extremum-seeking error field control minimizes three-dimensional magnetic fields in real-time to facilitate access to burning plasma conditions.

At the DIII-D National Fusion Facility (https://fusion.gat.com/global/DIII-D), scientists have developed a control algorithm for three-dimensional (3D) magnetic field optimization in tokamaks that can continuously respond to time-varying 3D field sources and plasma parameters. The magnetic field in a tokamak is nominally axisymmetric in the toroidal direction (the long way around the torus). However, in experimental devices, deviations from toroidal axisymmetry exist due to finite engineering tolerances, coil feeds and asymmetries, and nearby conducting structures. Through complex processes, these 3D "error fields" result in toroidal torques that brake the plasma rotation. The new algorithm exploits the link between minimizing deleterious error fields and maximizing the plasma rotation, which tends to improve both plasma stability and confinement. Continuously optimized control fields also facilitate access to high plasma current and low plasma rotation, a regime envisioned for burning plasma operation in ITER.

The new approach is based on extremum seeking control. Slowly-rotating fields, generated by external control coils, are used to modulate the plasma rotation, monitored in real-time using visible-light Doppler shift measurements. Signal processing of the applied fields and rotation measurements extracts the rotation gradient with respect to the control coil currents, which is used in a feedback loop to find the control coil currents that maximize the rotation. This approach can adapt to changes in the plasma equilibrium (a feature not found with existing methods), and can track time-varying error fields on experimentally relevant time scales.

In DIII-D, optimal correction for the most problematic magnetic error fields can be achieved with the new algorithm in a single discharge, making it suitable for long pulse devices and evolving plasma conditions. The maximum achieved angular momentum can exceed that found with preprogrammed estimates of the optimal currents derived from physics-based models and target equilibria (Figure 1), motivating further development of this technique.

While recent experiments have demonstrated the feasibility of the technique, further work is needed to reduce the convergence time (time to find the optimal currents) before the technique could be employed during early ITER operations. Extremum seeking methods tend to converge slowly, but faster convergence can likely be achieved by incorporating adaptive control methods. Simulation results show reduced convergence times for search trajectories in the coil current phase space parallel to the rotation gradient (Figure 2). Future work is aimed at incorporating these and other refinements in further experiments in DIII-D and the EAST superconducting tokamak in China.

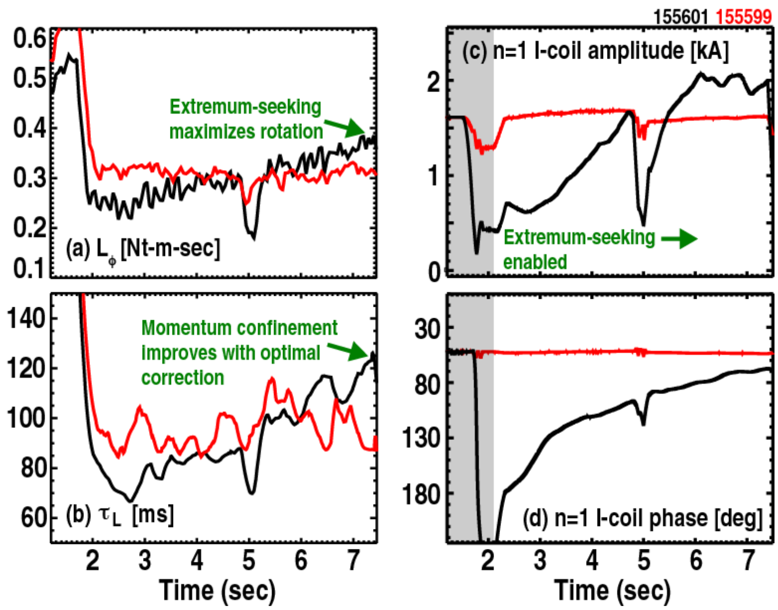

Figure 1. Time evolution of the (a) toroidal angular momentum (a measure of plasma rotation), (b) the angular momentum confinement time, (c) the time-averaged control coil amplitude, and (d) toroidal phase for two discharges: one with extremum seeking control enabled at 2.1s (black) and another with preprogrammed control currents (red) computed prior to the experiment using a target equilibrium and error field models.

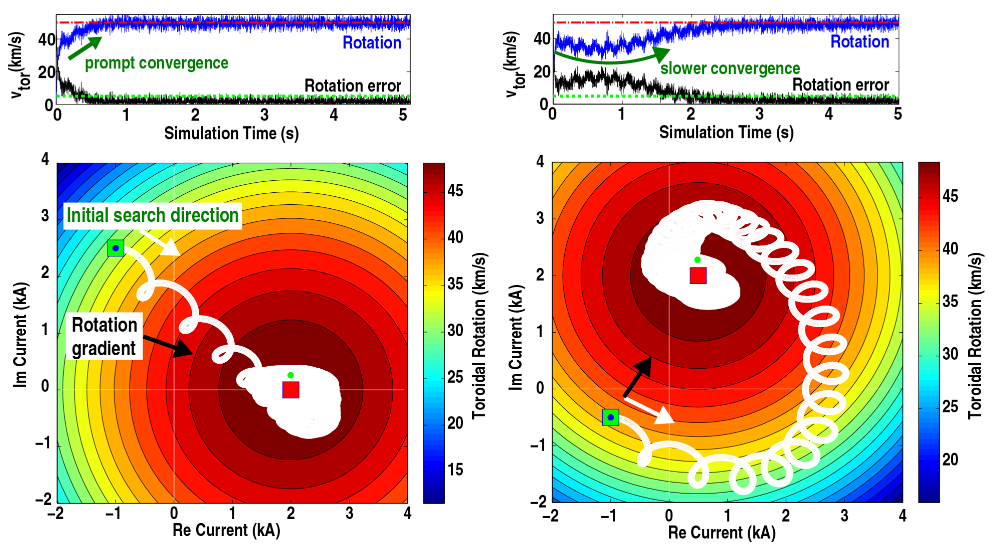

Figure 2. Simulations with extremum seeking control for two cases where the initial search vector is varied with respect to the rotation gradient. Contour plots (bottom) show the control coil current trajectory (white) plotted over contours of constant rotation. Line graphs (top) show the time evolution of the plasma rotation signal. The red dash-dot line is the optimal toroidal rotation (an input to the simulation).

Photo caption: (from left) David Humphreys, Matthew Capella, Michael Walker, Matthew Lanctot, Jeremy Hanson, Nick Eidietis, Erik Olofsson, Carlos Paz-Soldan, and Edward (Ted) Strait.