Plasma disruption avoidance using non-axisymmetric shaping with stellarator fields

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The avoidance and mitigation of major disruptions remains a critical challenge for ITER and future burning plasmas based upon the tokamak. The addition of small 3D magnetic field perturbations has been used for a variety of beneficial purposes on present day tokamak plasmas. Early stellarator experiments with toroidal plasma current were found to operate without disruptions if the vacuum rotational transform produced by external coils was greater than a threshold value of $\iota_{\mathrm{vac}}(a) \approx 0.14$ [1, 2].

Strong 3-D shaping produced by externally generated rotational transform is also observed to suppress disruptive phenomena of current-carrying discharges in the Compact Toroidal Hybrid (CTH), with the amount of rotational transform, $\iota_{\mathrm{vac}}(a)$, required for suppression dependent upon the disruption scenario. Current-driven disruptions are deliberately generated in CTH by (1) raising the plasma density, (2) operating at low edge safety factor q_a, or (3) by not compensating against the vertical instability of plasmas with high elongation. While the density limit is found to agree with the empirical Greenwald limit [3] at low edge vacuum transform $\iota_{\mathrm{vac}}(a) \approx 0.04$ the experimental densities exceed this limit by up to a factor of three as the vacuum transform is raised to $\iota_{\mathrm{vac}}(a) \approx 0.25$ without a threshold value of $\iota_{\mathrm{vac}}(a)$ observed for elimination of disruptions. Low q_a disruptions near $q_a \leq 2$ are observed at low vacuum transform but appear to have a threshold transform for avoidance, no longer occurring when the vacuum transform is raised above $\iota_{\mathrm{vac}}(a) \approx 0.07$ even though q_a falls well below

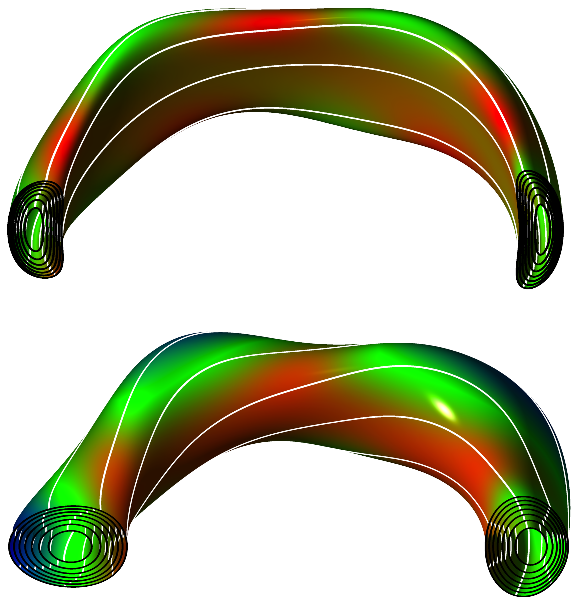

Figure 1: Reconstructed equilibira of a CTH plasma showing the highly shaped flux surfaces. Top: Vacuum equilibrium. Bottom: Hybrid equilibrium with 75 kA of plasma current. White lines are magnetic field lines, and colors are coded to indicate the magnetic field strength with red being high and blue low.

the value of 2. Passive suppression of the vertical instability of elongated plasmas is also observed with the addition of external transform, and the amount required is in qualitative agreement with an analytic calculation of marginal stability in current-carrying stellarators [4].

Introduction

CTH is a 5 field-period torsatron/tokamak hybrid with an $\ell = 2$, $n = 5$ helical winding to provide a vacuum transform profile with moderate shear, and an ohmic solenoid capable of driving plasma current $I_{\mathrm{plasma}} \leq 80\,\mathrm{kA}$, in stellarator plasmas established by electron cyclotron heating (ECH). An auxiliary set of toroidal field coils is used to vary the external rotational transform profile with accessible edge values in the range $\iota_{\mathrm{vac}}(\mathrm{a})$=0.02 - 0.3.

The shear of the external transform profile is varied with a set of quadrupole coils. The ECH system presently consists of three klystrons (one operating at 14 GHz and the others at 17.65 GHz) to produce a typical total input power of 15 kW. A 200 kW, 28 GHz gyrotron system has been implemented and tested into a dummy load, but not yet used in plasma experiments. Without ohmic heating, we obtain line-averaged densities of $\overline{n}_{\mathrm{e}} \leq 2.5 \times 10^{18}\,\mathrm{m}^{-3}$ and electron temperatures of $T_{\mathrm{e}} = 20\,\mathrm{eV}$ with broad profiles, while with ohmic heating the density may reach $\overline{n}_e = 5 \times 10^{19}\,\mathrm{m}^{-3}$, with a central electron temperature of $T_{eo} = 200\,\mathrm{eV}$.

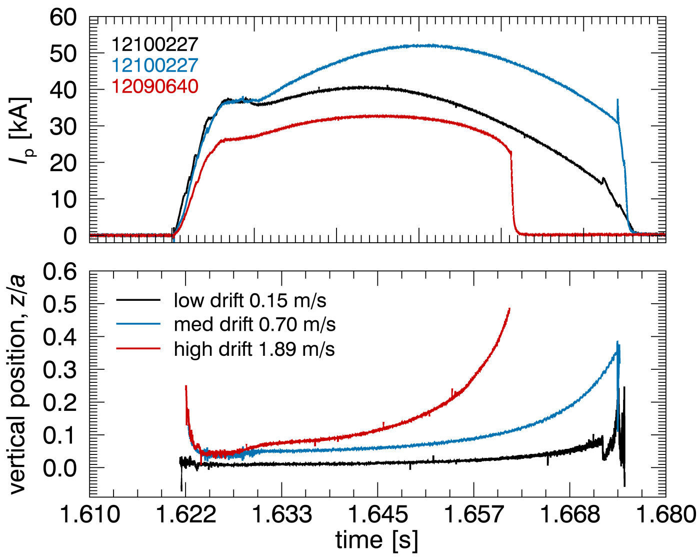

Figure 2: Three discharges with different amounts of vertical instability and consequently different drift rates. Top: Plasma current for each discharge. Bottom: Vertical position inferred from magnetic diagnostics.

Suppression of vertical instability

Disruptive terminations of current-carrying plasmas observed in CTH discharges generally fall into one of three categories: those due to vertical drifts (VDEs), density-driven disruptions, and disruptions that occur near $q_a = 2$. The magnitude of applied vacuum rotational transform is found to affect the occurrence of all three types. Due to the shaping provided by the helical coil current, CTH plasmas are vertically elongated both with and without plasma current (see Fig. 1), and it has been experimentally verified that they are subject to vertical drift instabilities as shown in Fig. 2. MHD predicts that the poloidal field from the stellarator equilibrium can passively stabilize the vertical drift. Fu [4] has found that the fraction of vacuum field, $\iota_{\mathrm{vac}}(\mathrm{a})$, relative to the total field, $\iota_{\mathrm{total}}(\mathrm{a})$, required for vertical stability depends on the average elongation of the plasma, κ, according to the relationship

$$f \equiv \frac{\iota_{\mathrm{vac}}(a)}{\iota_{\mathrm{total}}(a)} \geq \frac{\kappa^2 - \kappa}{\kappa^2 + 1}\,. \quad (1)$$

To test this relationship, a number of shots were taken in which the vacuum rotational transform and average plasma elongation were varied on a shot-to-shot basis. This ensemble of plasmas is shown in Fig. 3.

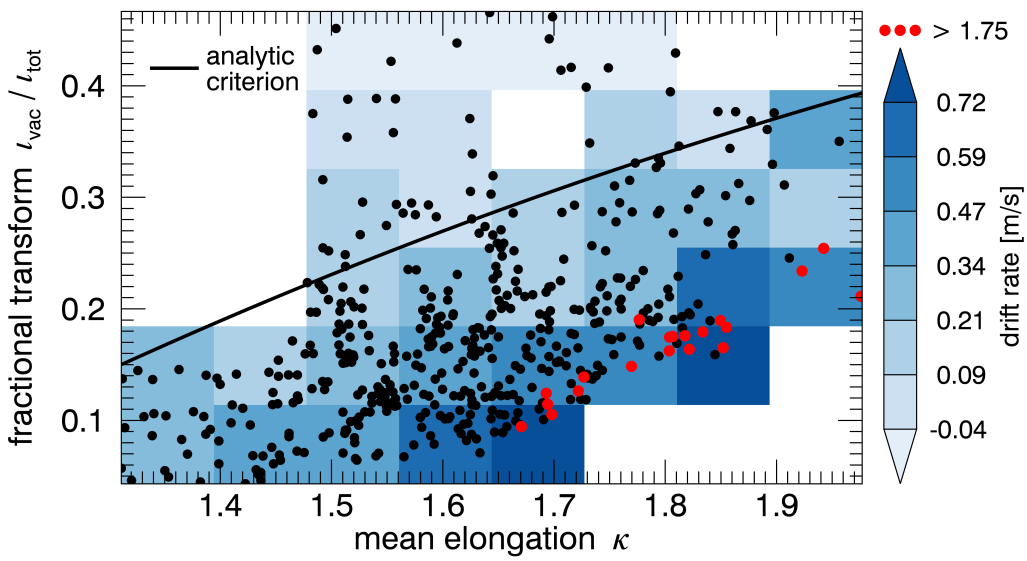

Figure 3: Scatter plot of discharges without vertical control. The shade of the blue squares represents the mean drift rate at time of peak plasma current for discharges falling within their bounds. A white space means that no data points in the averaging box. The red points are extremely unstable shots with $dz/dt > 1.75$ m/s and were excluded from the average to better illustrate the trend in the low drift rate data. The solid line is an analytic stability criterion with stability above and instability below. The solid line is the theoretical stability limit of Eq. (1)

Also displayed for comparison is the stability boundary given by Eq. (1). While there is some scatter, the analytic stability criterion separates the parameter region of low drift above the line from the higher drift region below.

Suppression of low q_a disruptions

High current plasmas are observed to disrupt when $q_a \leq 2$ for vacuum transform levels of $\iota_{\mathrm{vac}}(a) \leq 0.07$. When the vacuum transform is raised above $\iota_{\mathrm{vac}}(a) \geq 0.07$ these disruptions are suppressed as shown in Fig. 4. This disruption suppression has threshold behavior similar to the tearing mode suppression observed in earlier stellarator experiments [1] where the internal $m = 2$ and $n = 1$ mode was suppressed for vacuum transform levels higher than $\iota_{\mathrm{vac}}(a) \approx 0.14$. On CTH, these low q_a disruptions do not occur on initial crossing of the $q_a = 2$ surface, and typically have only weak $m = 2$ and $n = 1$ mode activity. When the $q_a = 2$ is in the vacuum just outside the plasma edge there is no significant $m = 2$ and $n = 1$ kink mode fluctuation observed. The edge q continues to evolve down to $q_a = 1.75$ and disruptions, when they occur, are preceded with strong $m = 3$ and $n = 2$ tearing activity. These tearing mode induced disruptions are suppressed for vacuum transform levels greater than $\iota_{\mathrm{vac}}(a) \sim 0.07$ as seen in Fig. 4.

Acknowledgments

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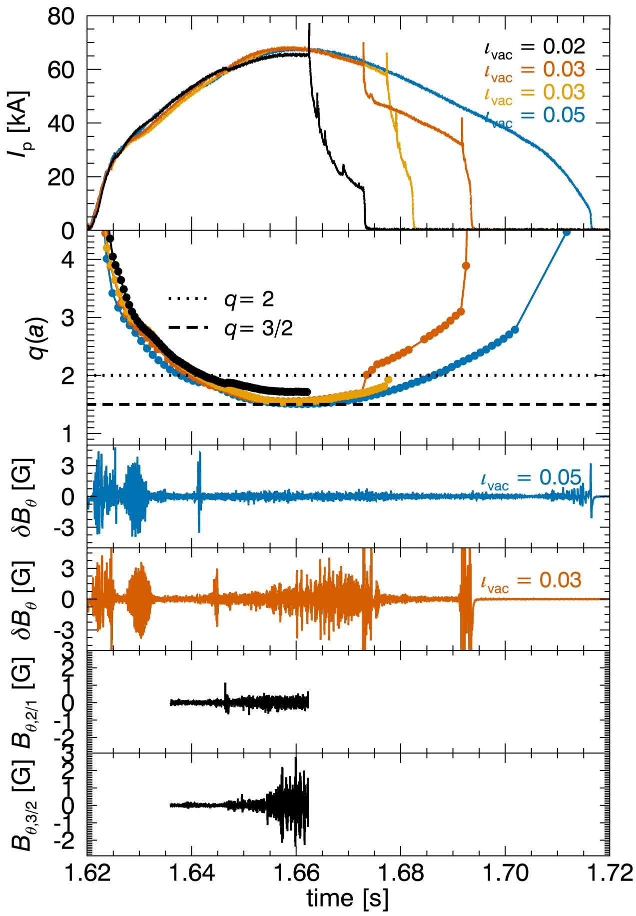

Figure 4: The vacuum and total rotational transform at which disruptions occurred, noting that low-q disruptions only occur for vacuum transforms below 0.07.