Overview of Results from the Compact Toroidal Hybrid Experiment

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Non-axisymmetric fields in the form of weak stellarator equilibria are found to modify the nature of disruptions in current-carrying toroidal discharges. Experiments on the Compact Toroidal Hybrid (CTH) demonstrate that disruptions in hybrid tokamak/torsatron discharges can be avoided in conditions that would lead to disruptions in tokamak plasmas. The Greenwald density limit is exceeded as the vacuum magnetic transform from the torsatron coils is raised. Plasma terminations due to vertical displacement events (VDEs) can occur if uncompensated in current-driven discharges, but become passively stable against vertical drift as the vacuum transform is raised. Interpretation of these results requires equilibrium modeling with non-axisymmetric capability, such as given by the V3FIT, 3D reconstruction code.

Introduction

Earlier experiments on stellarators have demonstrated the effect of external rotational transform of current-driven disruptions[1, 2]. In current-driven discharges in the W7-A and JIPPT2-M stellarators[1, 3], disruptions could be generated until the external transform was raised above a typical threshold value of $\iota_{\mathrm{vac}}(a) \approx 0.14$, where a represents the plasma minor radius. In recent studies on the Compact Toroidal Hybrid (CTH), we have also observed reduced disruptivity of hybrid discharges, and characterize them in relation to three distinct types of tokamak termination events: density limit, low-q_a ($q_a \leq 2$), and VDE disruptions.

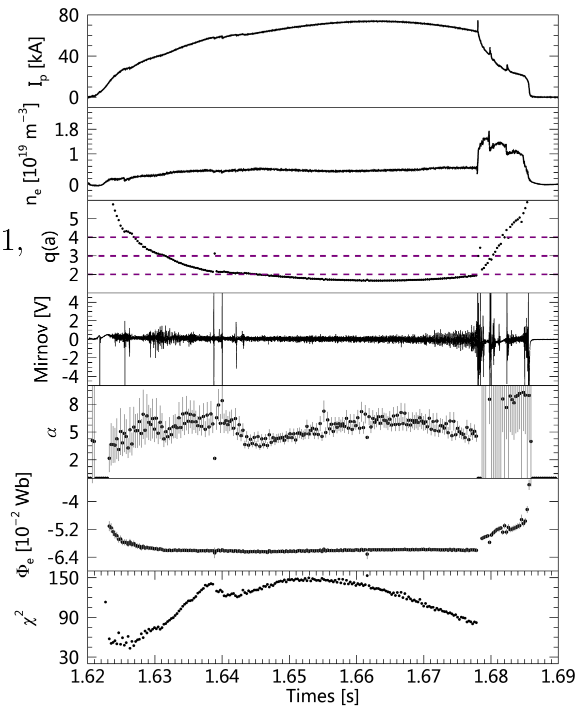

Figure 1: From top: plasma current, line-averaged density, edge safety factor, Mirnov signal (1 of 52), current profile parameter (see text), enclosed toroidal flux, and goodness-of-fit from a low transform shot.

CTH is a 5 field-period torsatron/tokamak hybrid with an $\ell = 2$, $m = 5$ helical winding to provide a vacuum transform profile with moderate shear, and an ohmic solenoid capable of driving plasma current $I_{\text{plasma}} \leq 80\,\text{kA}$, 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 $\iota_{\text{vac}}(\text{a})$=0.02 - 0.3. The shear of the external transform profile is varied with a set of quadrupole coils.

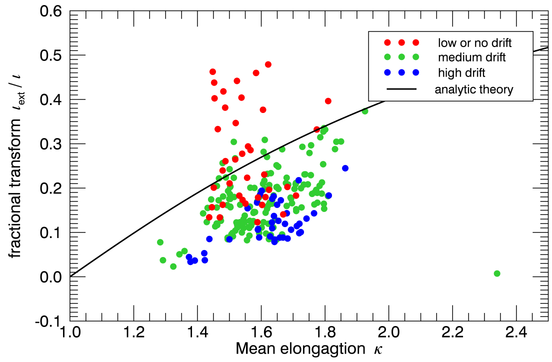

Figure 2: Scatter plot of the mean vertical elongation of CTH discharges and their fractional external transform (at maximum plasma current). Different colored symbols correspond to different rates of vertical drift. The solid line is the theoretical stability limit of Eq. (1)

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 $\overline{n}_{\text{e}} \leq 2.5 \times 10^{18}\,\text{m}^{-3}$ and electron temperatures of $T_{\text{e}} = 20\,\text{eV}$ with broad profiles, while with ohmic heating the density may reach $\overline{n}_e = 5 \times 10^{19}\,\text{m}^{-3}$, with a central electron temperature of $T_{eo} = 200\,\text{eV}$.

Reconstruction Analysis

Understanding MHD phenomena in the three-dimensional, highly shaped plasmas of CTH requires fully 3D reconstruction analysis techniques. The V3FIT[4] equilibrium reconstruction code is used to determine the MHD equilibrium most consistent with the magnetic diagnostic observations. The 3D MHD equilibrium is obtained with the VMEC[5] code. Fig. 1 shows a time-history of reconstruction results for a CTH discharge that happens to disrupt due to low q_a. Mirnov signals show increased activity when $q(\text{a})$ drops through integer values, where $q(\text{a})$ is determined from the converged equilibrium of the reconstruction at each time slice. In this case, the main reconstruction parameter of interest is the width of the plasma current profile given by α, where the current profile is parameterized as $J(s) = J_o(1 - s^{\alpha})^6$ with s being a flux surface label. The current profile is broad during the current ramp-up and peaks just after the safety factor drops below $q(\text{a}) = 2$. The total toroidal flux enclosed by the last closed flux surface is Φ_e. The trend of the χ^2 values indicate the existence of a uncompensated systematic error.

Disruption Suppression Studies

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, and it has been experimentally verified that they are subject to vertical drift instabilities or VDEs. MHD predicts that the poloidal field from the stellarator equilibrium can passively stabilize the vertical drift. Fu [6] 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

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

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. These results are shown in Fig. 2 in which the rate of the observed vertical drift was characterized as low or nonexistent (red points), medium (green points), or high (blue points). 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.

As in tokamaks, disruptions are observed in CTH plasmas of given plasma current

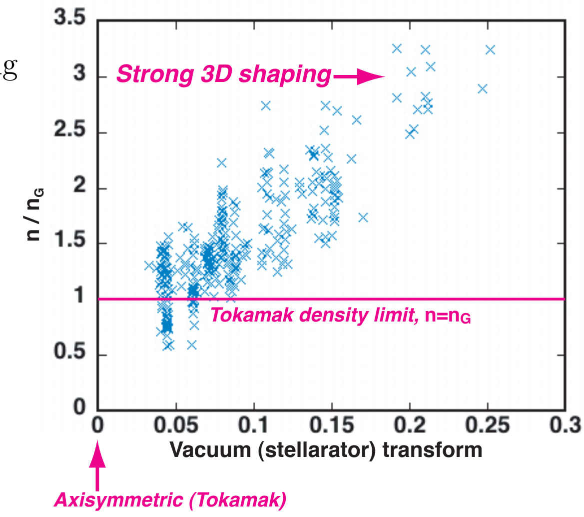

Figure 3: The density at which the disruption occurs normalized to the tokamak density (Greenwald) limit as a function of the external rotational transform.

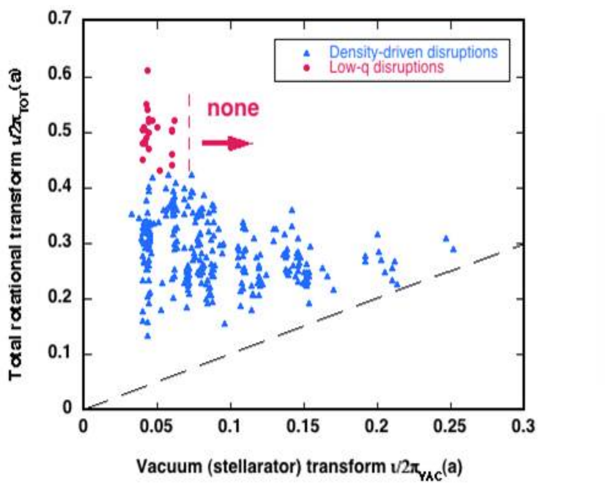

Figure 4: Scatter plot of disrupting shots organized by vacuum and total rotational transform. The dashed black line denotes a current-free stellarator equilibrium. Low-q disruptions (red) do not occur above an applied vacuum transform of 0.07.

when the density is raised above threshold values. In tokamak devices the Greenwald [7] limit to the density is a function of the plasma current and horizontal semi-minor radius $\overline{n}_G \equiv I_p/\pi a^2$.

In current-driven CTH discharges in which external rotational transform is imposed, the disruption densities no longer conform to the Greenwald scaling, but can exceed it by over a factor of three at the maximum level of external transform applied. The disruption densities normalized to the Greenwald limit for a number of shots is plotted as a function of the imposed vacuum (stellarator) rotational transform in Fig. 3. When the applied vacuum transform is near zero, the disruption density matches the value expected from the Greenwald limit, but the normalized limiting density increases as the amount of external transform increases. When CTH densities remain below their disruptive limits and when vertical drifts are suppressed, we have observed disruptions in high current discharges when the value of the edge safety factor is near $q_a = 2$. Typically in disruptions of this type, the plasma current often recovers and an increase in density is observed just after the disruption. Fig. 4 shows a compilation of shots as a function of their total rotational transform and vacuum transform. Density-driven disruptions are shown in blue and those that disrupted when the $\iota_{\text{total}} = 0.5$ surface is at the edge are shown in magenta. Thus far, low-q disruptions only occur in CTH when $\iota_{\text{vac}}(a) \leq 0.07$.

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