Disruption avoidance in current-carrying tokamak/stellarator discharges in CTH

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Abstract

Experiments performed on the Compact Toroidal Hybrid (CTH) aim at understanding the suppression of the disruptive instability in hybrid torsatron/stellarator discharges. Density and current-driven disruptions do not occur when the vacuum rotational transform from the stellarator field coils is raised above a threshold value. Vertical drift of the current-carrying plasma is usually observed, and will be compensated for in future experiments.

Introduction

Prior to the development of high power radio-frequency and neutral beam heating, stellarator discharges were often heated with ohmic plasma current. Results from several of these early stellarator experiments demonstrated that the occurrence of current-driven disruptions was eliminated if the vacuum rotational transform $\iota_{VAC}(a)$ at the plasma surface, i.e. the transform produced by the external currents of the stellarator coils at the plasma minor radius *a*, was greater than a threshold value of $\iota_{VAC}(a) \cong 0.14$.[1,2] Moreover, current-driven stellarator discharges with a net transform $\iota_{TOT}(a) \geq 0.5$ could be generated without exciting an unstable external kink mode. Because of the need to reduce the consequences of major disruptions in ITER and future burning plasma devices, the robust disruption resistance of the hybrid stellarator may lead to a significant improvement of the tokamak fusion reactor concept.[3] Moreover, there has developed a renewed interest in the stability and equilibrium properties of current-carrying stellarators due to the generation of finite bootstrap current in high-beta stellarator discharges, and the exploration of advanced quasiaxisymmetric stellarator designs in which a significant level of bootstrap current is required for the optimization of stability and confinement.[4] While stellarator configurations allow for excellent confinement in largely current-free discharges, they may also provide the means of improving toroidal confinement more generally.

Experiments are underway in CTH to investigate the causes and limits of disruption avoidance in hybrid stellarator-tokamak discharges. CTH is a low aspect ratio ($R/a \leq 4$) $l = 2$ torsatron with a vacuum rotational transform capable of being varied in the range $0.02 \leq \iota_{VAC}(a) \leq 0.4$ with auxiliary toroidal field coils. The toroidal field strength of $B_0 = 0.64$ T is matched to the fundamental resonance of the 17.65 GHz klystrons for electron cyclotron resonant heating ($P_{\mathrm{ECRH}} = 20$ kW). The shear of the vacuum transform (and the average vertical plasma elongation) is also variable with the use of quadrupole field shaping coils. Ohmic plasma currents up to $I_p = 65$ kA are induced in ECRH-generated stellarator target discharges.

Disruptions can be generated in current-driven CTH discharges by exceeding a safety factor limit or an electron density limit, as in tokamaks. Furthermore, ohmic plasmas in CTH are also subject to vertical displacement events (VDE), as they are typically elongated in the vertical plane. VDEs in CTH can lead to a disruption late in the discharge as the plasma shrinks against the upper limiter. However, disruptions of any kind are not observed if the vacuum transform of the configuration exceeds a value $\iota_{VAC}(a) \approx 0.11$, more or less in agreement with earlier results from W7-A[1] and JIPPT-2.[2] We note that the average β values of CTH are only on the order of 0.1%, and therefore high-β disruptions are not expected.

Disruptions

A density-driven disruption in a discharge with $\iota_{VAC}(a) = 0.04$ is shown in Fig. 1. The line-averaged density is increased by gas puffing until a disruption occurs, as identified by the sudden increase in plasma current and negative loop voltage spike. The density is maintained above the ECRH cut-off density after the disruption (although the interferometer loses several fringes following the disruption). The plasma current decays to zero over a period of several milliseconds. A growing m=2/n=1 oscillation is present prior to the disruption, indicating the disruption is associated with a tearing mode-unstable current profile.

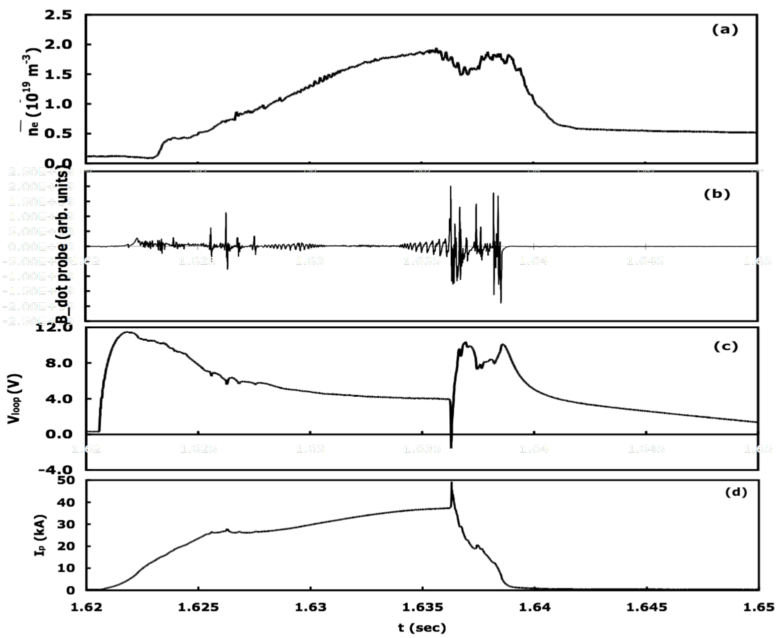

Fig. 1 Evolution of plasma parameters of discharge terminated by density-driven disruption. (a) line-averaged density, (b) Mirnov coil output (1 of 32), (c) loop voltage, (d) plasma current.

Similar density-driven disruptions are found to occur in CTH for vacuum rotational transform values up to $\iota_{VAC}(a) \approx 0.11$. The density of observed disruptions, normalized to the nominal Greenwald density limit[5] is plotted vs. vacuum rotational transform in Fig. 2. Above the apparent threshold value of the rotational transform, the plasma current declines as the density is increased, indicating a cooling of the plasma, but does not disrupt.

The elimination of high-current disruptions is illustrated in Fig. 3 in which the current traces of three discharges with different vacuum rotational transforms are plotted. While the edge transform of all three discharges evolves to exceed 0.5 at the plasma boundary, based on equilibrium reconstruction, only the discharge with the lowest vacuum rotational transform of $\iota_{VAC}(a) = 0.03$ actually disrupts. Unlike density-driven disruptions on CTH, the high-current disruption exhibits a rapid quench of the current. In this case, a growing m=3/n=2 MHD precursor appears 5msec prior to the disruption. For the discharges with the higher background rotational transform, the net edge rotational transform evolves to exceed $\iota_{TOT}(a) = 0.5$ to reach a maximum near $\iota_{TOT}(a) \cong 0.75$ in MHD-stable discharges.

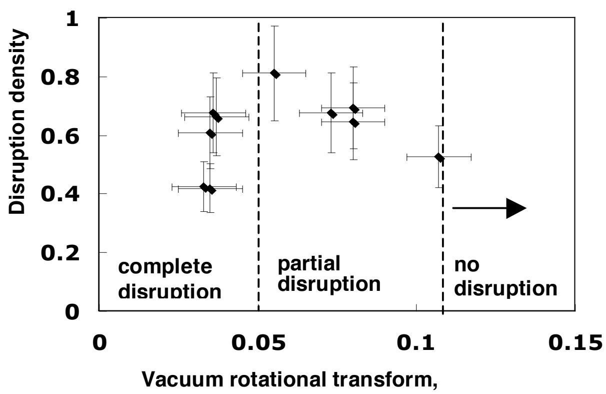

Fig. 2. Line-averaged density at disruption vs. $\iota_{VAC}(a)$. Density normalized to the Greenwald density limit, $I_p/\pi\langle a\rangle^2$

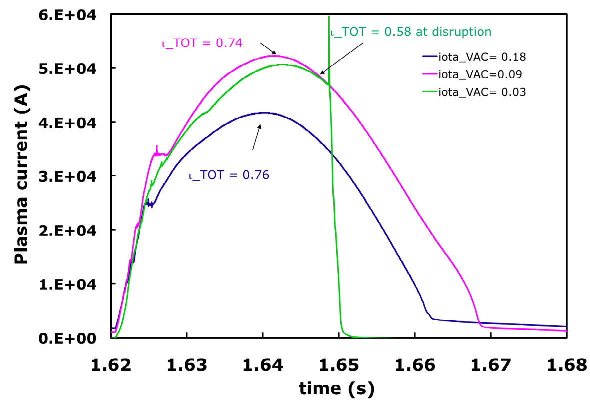

Fig. 3. Plasma current for three discharges with varying vacuum rotational transform

Depending on the magnitude of the vacuum transform, high-current discharges undergo a vertical drift (VDE). G. Y. Fu has calculated the vertical stability of current-carrying stellarator plasmas in ideal MHD and found an analytic condition for the fraction of external rotational transform required for passive stabilization of stellarator plasmas with vertical elongation κ:[6]

$$f \equiv \frac{\iota_{VAC}(a)}{\iota_{TOT}(a)} \geq \frac{\kappa^2 - \kappa}{\kappa^2 + 1} \qquad (1)$$

In CTH, the vertical elongation varies with the vacuum rotational transform, and can also be controlled with a shaping poloidal field coil set independent of the other equilibrium coils. Furthermore, an additional poloidal coil set is available for vertical position control, but has not yet been used in a feedback mode to do so. The experimental value of the toroidally-averaged elongation is computed with the VMEC equilibrium code within the 3D reconstruction procedure.[7] Typical flux surfaces showing the plasma elongation with and without plasma current are illustrated in Fig. 4 at the two planes of vertical symmetry of the toroidal plasma (ϕ = 0˚ and 36˚).

The minimum value of *f* that is observed for a given elongation (evaluated at the maximum plasma current in a given discharge) in a series of discharges is plotted in Fig. 5, along with the analytic relation of Eq. (1). The results show a clustering of the data near the limiting condition given by Fu, although there remains a considerable scatter in the results. The evolution of the current in discharges set up with high vacuum elongation was often unsuccessful to due to high rates of vertical drift. An important point is that vertical displacement of the stellarator discharge complicates the understanding of the elimination of density and current-driven disruptions at low vacuum transform, particularly since a non-vertically symmetric 3D reconstruction procedure is not yet available to model these discharges. Future work is oriented to controlling the vertical position with a feedback-driven power amplifier energizing a pair of radial field coils.

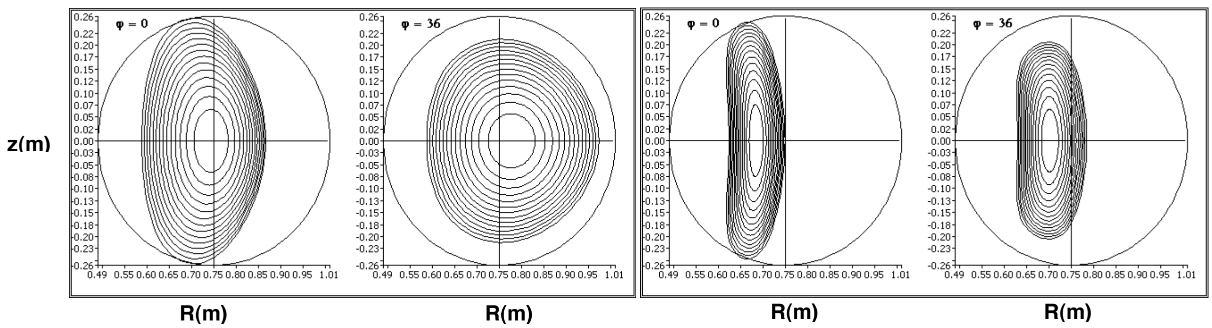

Fig. 4. Equilibrium flux surfaces computed from VMEC: (left) I_p= 30 kA, and (right) I_p= 0.

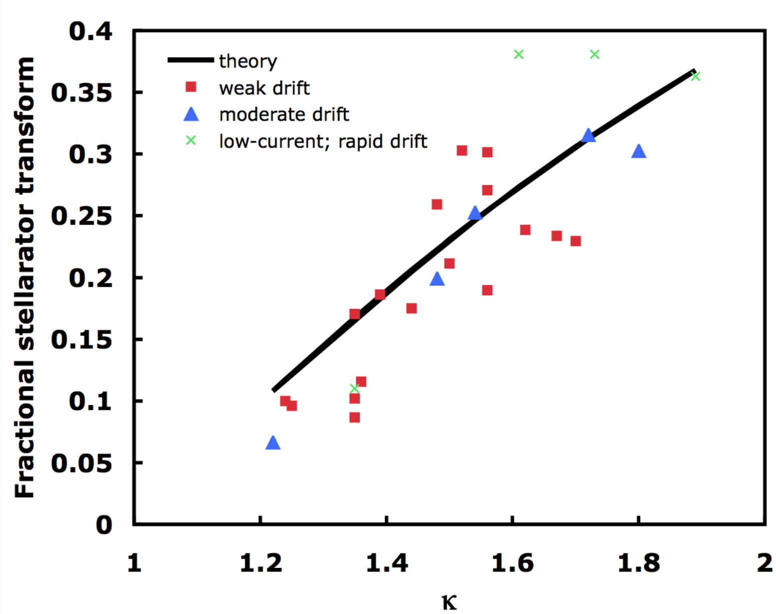

Fig. 5. Fractional rotational transform achieved vs. average κ in current-driven discharges.

Acknowledgements

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